Study on the use of Wi-Fi for Metropolitan Area applications

Final Report for Ofcom

2509/WMAN/FR/V1

22nd April 2013

ÆGIS spectrum engineering

Quotient Associates

Table of Contents

0 EXECUTIVE SUMMARY

0.1 Background and Context

This report describes a study undertaken for Ofcom on the use of Wi-Fi for wireless metropolitan area networks (WMANs). The main purpose of the study was to investigate the status of the Wi-Fi co-ordination, interworking and roaming technologies and the potential implications for Wi-Fi spectrum utilisation. We have undertaken an extensive review of technology developments in these areas and analysed three specific deployment scenarios to generate estimates of Wi-Fi spectrum demand over the medium to long term (2024).

0.2 Wi-Fi Technology Evolution

0.2.1 Co-ordination Methods

Early Wi-Fi networks operated without any centralised control, with individual stations controlling access to the medium. This is still generally the case in home environments, but for enterprise and WMAN deployments Wi-Fi has taken a different turn. New 802.11 standards allow stations to be aware of their environment via measurements and to support handover in a quicker, more seamless way. The relevant standards are 802.11k, 11r, 11v and 11w, all of which have been incorporated into the latest IEEE 802.11-2012 standard.

802.11k, concluded in 2005, covers access point (AP) measurements and has been adopted quite widely by AP vendors and increasingly by the client device community. 802.11v was ratified in 2011 and allows AP measurements to be used in order to enable centralised remote configuration of client device parameters, but adoption so far appears to be low. 802.11r reduces the handover time between APs and enables fast seamless roaming for real time applications such as VoIP. 802.11w improves network security and helps ensure the reliability required by real time services.

These 802.11 extensions alone are not sufficient to create a managed network. A network management entity must sit above these interfaces and provide the control function. The latter has been developed in a proprietary manner by companies such as Cisco and Ruckus and encompasses a number of common techniques, including

- Band steering, which pushes dual band enabled users to 5 GHz where available;
- Client Steering, which enables APs to steer unwanted clients away by refusing to accept connections;
- Active channel selection, to select automatically less congested RF channels;
- Air interface restrictions, e.g. restricting access for less efficient legacy devices, notably 802.11b;

- Smart antennas / beam steering, which enable a wanted signal to be maximised, while unwanted signals (which are assumed to be in other directions) are minimised.

These co-ordination methods suffer some limitations, depending on the environment in which they are deployed. These include:

- Legacy client device performance problems, which are likely to be a particular issue in the WMAN and residential sectors
- Limited scalability, since co-ordination methods tend to be simple, rules based approaches, often working close to the physical layer which may not scale to larger networks.

Recent developments in interworking and roaming (described below) have begun to address both these limitations, although simple co-ordination methods may remain most appropriate for small Wi-Fi networks, such as home networks.

0.2.2 Interworking and Roaming Methods

There have been three key initiatives in this area, namely:

- Hotspot 2.0, from the Wi-Fi Alliance;
- Access Network Discovery and Selection Function (ANDSF), from 3GPP;
- Next Generation Hotspot (NGH) from the Wireless Broadband Alliance.

Hotspot 2.0 from the Wi-Fi Alliance is designed to simplify ease of connection from the user's point of view and to ensure security of transmitted data. The specification supports four standard authentication protocols commonly deployed in the industry

- EAP-SIM – for devices with SIM credentials;
- EAP-AKA – for devices with USIM credentials;
- EAP-TLS – for use with a trusted root certificate;
- EAP-TTLS with MSCHAPv2 – for user-name / password credentials.

This range caters for Wi-Fi devices with and without SIM cards. The WFA is already certifying Hotspot 2.0 phase 1 devices. A logical business case extension of the Hotspot 2.0 approach could be a move to wholesale provision of Wi-Fi as a Service, as Virgin Media is already doing on the London Underground, for example.

ANDSF is intended to extend a degree of control by mobile operators over which Wi-Fi networks a device will preferentially attach to. It is not however intended to perform real time network selection and may conflict with the device connection manager, which is currently a source of uncertainty for the future prospects of the standard.

NGH is a collection of initiatives including a program of testing the interoperability of WFA PassPoint™ certified equipment with carriers' back-ends. One reason this is important is that Hotspot 2.0 works in an abstracted, pre-authentication mode to identify service providers, whereas ANDSF works directly with SSIDs to identify service providers. Work to integrate Hotspot 2.0 and ANDSF policy operation is on-going.

We expect that authentication seamlessness, as facilitated by initiatives such as these, is likely to have a significant positive effect on the uptake of Wi-Fi offload, as it removes a key barrier. The reason that hotspot usage stands at a relatively low percentage has been directly attributed to this usability barrier. Session seamlessness is initially likely to be important to only a relatively small proportion of users, but its importance is expected to grow as more real time services such as voice over IP are taken up.

Alternative approaches to roaming, based on the use of specially modified routers which enable users to access each other's access points, have been pioneered by the Spanish company FON and the Swedish company AnyFi. FON has partnered with BT in the UK to create a network of over 4 million BT subscriber access points that can be accessed by other BT FON subscribers or BT's Wi-Fi roaming partners. It is questionable however whether these provide a realistic substitute for WMANs due to the limited outdoor range of the indoor access points.

There are two key areas of uncertainty related to the market penetration of the various interworking approaches. Firstly there is a mismatch between the Hotspot 2.0 pre-authentication paradigm which dispenses with the need for SSIDs during network discovery, versus the continuing key role of SSIDs within ANDSF. This is currently under study. Secondly the implementation of the connection manager software by device manufacturers is presently not standardised and leads to issues such as sticky clients and potential conflicts concerning handovers, for example between user and carrier roaming preferences.

0.2.3 Implications for future spectrum efficiency

We have identified seven key developments that may have an effect on future spectrum efficiency in Wi-Fi networks, namely:

1. 802.11 extensions (k, r, v, w)
2. Adaptive antenna modules
3. Load balancing by client or band steering
4. Guided channel selection
5. Reduction of broadcast overhead via Hotspot 2.0 pre-association discovery
6. Load balancing and offloading – via interworking protocols, e.g. Hotspot 2.0, ANDSF.
7. Connection manger effectiveness and uniformity.

These are described in detail in the main report (section 2.4). The likely applicability of the potential spectrum efficiency improvements for each deployment is shown below.

Table 0-1 Applicability of efficiency approach versus deployment type

Approach >	1	2	3	4	5	6	7
WMAN		X	X	X	X	X	X
Hotspots		X	X	X	X	X	X
Enterprise	X	X	X				X
Residential		X		X			X

0.2.4 802.11 ac

The latest 802.11ac standard is intended to provide substantially higher speed and one of the ways this is achieved is via wider channels of 80 and 160 MHz. Unlike 11n, a fall back to narrower channels on a per-frame basis is mandated in the 11ac draft standard, such that fairness of medium access is offered to legacy 20 and 40 MHz channel devices. However, if wider channels are to be used successfully, then sufficient free bandwidth needs to be available, such that contention and hence fall back may be avoided. In Quotient's earlier work for Ofcom, this was seen as a key driver for expanding the amount of contiguous spectrum available at 5GHz for Wi-Fi.

0.2.5 802.11 High Efficiency Study Group proposal

Very recently a proposal was put forward to create an IEEE 802.11 High Efficiency study group, which is expected to address the issues of high density WLAN deployments and may include the additional considerations of multi-operator environments.

0.3 Current Status of WMAN Deployments

We have identified a number of existing and planned deployments of Wi-Fi WMAN networks in the UK, including:

- **Virgin Media:** indoor network serving London Underground stations and outdoor network serving Leeds and Bradford city centres. Further outdoor networks planned.
- **BskyB / The Cloud:** outdoor network serving the City of London. Also operates a large network of indoor Wi-Fi hotspots.
- **Telefonica / O2:** outdoor networks serving various locations in central London. Also operates a large network of indoor Wi-Fi hotspots.
- **BT Wi-Fi:** outdoor networks serving several city centre locations. Also operates a large network of indoor Wi-Fi hotspots and over 4 million shared residential access points operated in conjunction with Spanish company FON.
- **Global Reach:** operates an outdoor network along the River Thames in London that provides access to BT Wi-Fi subscribers and river users.

- **Bristol:** public WMAN joint venture between Bristol City Council and Bristol University

Other examples of Wi-Fi MANs include an extensive municipal network in Barcelona, a large number of smaller scale networks in Spain and a number of FON-supported shared access networks in other European countries. Outdoor networks have also been widely deployed in the US and many other countries around the world, although in some cases networks have closed due to funding difficulties (in the case of some municipal networks) concern from other operators about unfair competition. There have also been some failed WMAN initiatives in the UK, for example in Islington and Swindon.

0.4 Current Status of Wi-Fi Frequency Bands

Our research has shown that the overwhelming majority of current Wi-Fi deployment, particularly in the residential sector, is at 2.4 GHz. There has however been a significant push towards dual band systems for public Wi-Fi hotspots and WMANs, with the UK's two largest providers both deploying 5 GHz throughout their networks and seeing increasing traffic in this band.

Otherwise it appears that the existing 2.4 GHz band is still proving sufficient to meet current demand in most situations, despite having only three non-overlapping 20 MHz channels (compared to nineteen in the 5 GHz band). However, we expect to see substantial growth in the deployment of dual band systems over the next few years, to support projected traffic growth and support bandwidth hungry applications like high definition video.

Both the 2.4 GHz and 5 GHz bands are shared with other services. At 2.4 GHz, these are generally low power short range applications like Bluetooth and ZigBee which tend to co-exist well with Wi-Fi networks. Interference from microwave ovens and analogue video senders or baby monitors can be more of a problem but tends to be limited to the centre part of the band. These interference sources are usually located indoors hence less likely to affect outdoor WMAN deployments. At 5 GHz the other principal use is radars and Wi-Fi systems in the affected part of the band are required to use dynamic frequency selection to avoid frequencies that are used by local radars. This constraint does not yet appear to have had any significant impact on the ability to use these frequencies in the UK but may become an issue at some locations in the future.

0.5 Analysis of Potential Wi-Fi Spectrum Demand and Benefits of Technology Enhancements in various Wi-Fi Deployment Scenarios

The potential demand for Wi-Fi capacity and radio spectrum in three typical operational scenarios has been analysed, taking account of projected traffic levels for various user categories (business, residential, public hotspot, outdoor WMAN), estimated throughput capacity per AP and estimated spectrum re-use capability.

The three deployment scenarios considered were:

i) Dense urban location with a mix of business, residential, indoor hotspot and outdoor MAN deployments

ii) High density residential building

iii) Business Park with high density enterprise network

For the first scenario we chose a real location with a particularly high level of Wi-Fi deployment. The other two scenarios are more hypothetical and we have used a modelling approach to estimate the degree of contention and spectrum re-use that might arise. A detailed description and analysis of the three scenarios is presented in chapter 5 of the main report,

The table below summarises our estimates of the potential spectrum demand for the year 2024 in each of the three scenarios we have analysed

Figure 0-1 Summary of spectrum demand estimates

Traffic Type	Scenario 1	Scenario 2	Scenario 3
Residential use	240	280	0
Business use (indoor)	120	0	200
Business use (outdoor)	0	0	120
Public use (indoor)	100	0	0
Public use (outdoor - WMAN)	80	40	40
Meshing of outdoor access points	80	40	40
Total potential spectrum requirement	**620 MHz**	**360 MHz**	**400 MHz**

Comparing these forecasts with the spectrum that is currently available in the Wi-Fi frequency bands (440 MHz of usable spectrum in total), we find that in the mixed urban scenario there is a potential 180 MHz shortfall, whereas in the other scenarios there appears to be adequate spectrum to meet the projected demand. However, this assumes that the entire allocated 5 GHz spectrum is available, whereas in practice at some locations some of the channels may be unavailable in order to protect local radar stations.

We also note that the current fragmentation of the 5 GHz band is likely to constrain the extent to which wider channels (80 MHz or 160 MHz) could be deployed under the new 802.11ac standard and would recommend that any additional spectrum to meet the identified shortfall should be ideally be located adjacent to the existing 5 GHz bands to maximise the amount of contiguous spectrum available.

It should also be noted that there is a high degree of uncertainty in attempting to project future spectrum demand to support Wi-Fi traffic. These uncertainties include the level of future wireless traffic and the potential impact of longer term demand for the higher bit rates (and correspondingly wider channels) provided by the new 802.11 ac standard. Note that our projections are based on anticipated traffic levels in 2024 and that continuing growth in wireless data traffic beyond that date may also create demand for additional spectrum.

0.6 Conclusions

Our findings suggest that the impact of enhanced AP co-ordination on overall spectrum demand is likely to be small, largely because such enhancements are unlikely to be adopted to any significant extent in the residential market, which in the long term we expect to dominate demand for Wi-Fi spectrum. Even in enterprise networks, the scope for substantial improvements in spectrum efficiency is limited, albeit to a lesser extent, due to the need to support a wide mix of client devices, via the BYOD[1] effect. Although enhancements such as 802.11k are being adopted in the latest generation of public WMAN deployments, the industry perception is that any benefits will be limited due to the inconsistent way that these enhancements are likely to be adopted by device vendors.

A more promising development in terms of improving spectrum efficiency is the wider deployment of beamforming techniques to provide better targeted coverage, improved signal quality (and hence throughput) and reduced contention between nearby access points. Vendors claim an overall throughput improvement of as much as 70% is feasible, although it is unclear what assumptions underpin this estimate.

Dynamic channel management protocols have also been adopted in a number of WMAN deployments to enhance performance and capacity, particularly in the congested 2.4 GHz band. Capacity improvements of 25 – 50 % have been claimed, but again it is unclear what assumptions have been made in arriving at this estimate.

In general we caution that the deployment of unmanaged optimisation methods such as beamforming and dynamic channel assignment may be open to unintended consequences with respect to their operation in some dense, mixed capability, multi-operator environments. This is because there is, in general, no guarantee that independent optimisations will lead to a stable network level optimisation. However it is perfectly conceivable that specific future work could dispel concerns in this area.

In terms of future demand, there is much uncertainty surrounding the level of traffic that might be carried over Wi-Fi networks in the future, particularly for public Wi-Fi networks (hotspots and WMANs). It seems likely however that such traffic will remain relatively small compared to that carried over residential and larger enterprise networks. Interworking advances (such as Hotspot 2.0) may lead to

---

[1] The Bring Your Own Device effect means that the enterprise network, which was previously a well defined walled garden, now increasingly has to cope with an influx of a range of user devices, including not only clients but potentially users' APs via for example mobile Wi-Fi hotspots or Wi-Fi Direct™.

substantially increased demand (albeit from a very low base), but will also have the capability to help avoid inefficiencies with respect to how this demand be handled by networks in the future.

Other technology enhancements still suffer uncertainties with respect to their effect on demand. Several aspects of Wi-Fi operation remain implementation independent including the device connection manager. A possible implication is that the 3GPP backed ANDSF initiative may not succeed in the market because there will be resistance to its operation from end users and device manufacturers. This is due to conflicts over end user ownership, such as when user, mobile operator and Wi-Fi operator connection preferences and policies conflict. For example, the user may prefer one network, such as a home or office network, the mobile operator stored policy may promote a network with which a commercial agreement exists and the Wi-Fi operator may present a third option. The connection manager also leads to 'sticky' handover behaviour in some implementations. New standards work is just beginning in this area, within the Open Mobile Alliance (OMA) and the IETF, which we have suggested that Ofcom follows.

We also suggest that Ofcom follows the very recent proposal to create an IEEE 802.11 High Efficiency study group, which is expected to address the issues of high density WLAN deployments and may include the additional considerations of multi-operator environments.

1 BACKGROUND AND CONTEXT

This report describes a study undertaken between January and April 2013 by Aegis Systems Limited and Quotient Associates for Ofcom on the use of Wi-Fi for metropolitan area applications. The main purpose of the study was to investigate the current status of the technologies available to support Wi-Fi Access Point (AP) co-ordination, interworking and roaming between Wi-Fi and cellular networks, the extent to which these are being deployed in the market and the likely impact of future evolution of these technologies on utilisation of the Wi-Fi bands.

Metropolitan Area Networks (MANs) are defined by the IEEE as being "optimised for a larger geographical area than a LAN, ranging from several blocks of buildings to entire cities"[2]. Wireless MANs are technically more challenging than WLANs since users may connect to the network via multiple access points and to gain the full benefit of the wide area coverage an effective handover process between APs is required. Where the MAN is used to provide offload from a cellular network an effective roaming capability between the two is also desirable.

In chapter 2, we review the progress that has been made to date, both in the international standards fora and by individual equipment vendors, to meet these challenges.

There are a number of WMANs already operational in the UK, for example:

- **BT** enables its home broadband subscribers to opt-in to an arrangement which allows them to connect via the access point of any other opted-in subscriber, effectively creating over 4 million Wi-Fi hotspots that can be accessed by BT subscribers.
- **The Cloud**, owned by BskyB, operates over 16,000 indoor Wi-Fi hot spots across the UK and operates an outdoor WMAN in the City of London
- **O2 Wi-Fi** operates over 7,000 indoor Wi-Fi hot spots across the UK and operates outdoor WMANs in a number of central London locations.
- **Virgin Media** operates an outdoor WMAN in the centres of Leeds and Bradford and also has an exclusive arrangement to provide public WiFi at stations on the London Underground network.

We discuss the technical and business approaches taken by these and other WMAN operators in more detail in chapter 3.

Wi-Fi based WMANs provide an opportunity to offload data traffic from mobile cellular networks in areas or at locations where traffic demand is particularly high. Conventional cellular networks can struggle to cope with demand in such scenarios

[2] IEEE Standard 802-2001 for Local and Metropolitan Area Networks: Overview and Architecture

due to the relatively large cells that are deployed (to ensure continuity of coverage) and the limited availability of radio spectrum. Small cell networks, whether Wi-Fi based or using cellular technology, offer significantly greater capacity but are more limited in terms of mobility. However, the use of licence exempt spectrum (e.g. in the Wi-Fi bands) for small cell networks may be challenging in that this spectrum is also increasingly heavily used by private Wi-Fi connections and other radio applications, which may limit the data traffic that can be accommodated at some locations. In consequence there may be a need for additional spectrum to support such applications in the longer term.

In chapter 4 we review the current status of the existing Wi-Fi bands, in terms of the extent to which they are used by Wi-Fi and other wireless applications. In chapter 5 we describe three typical high density deployment scenarios for WMANs and consider the implications for future spectrum demand, taking account of projected traffic levels, potential to re-use Wi-Fi frequencies and anticipated developments in Wi-Fi technology.

The conclusions of our study are presented in chapter 6.

2 WI-FI TECHNOLOGY EVOLUTION

2.1.1 Introduction

In this Chapter, we examine Wi-Fi networking advances in two areas, namely

- Co-ordination;
- Interworking and roaming.

Firstly, we examine those advances which are primarily based on co-ordination. Implicit in many of the co-ordination methods, which employ both 802.11 extensions and proprietary methods, is that a single Wi-Fi network is being considered. This is in the sense that the network, although it may be extensive, is under the control of a single central management function. Secondly, we look more widely at Wi-Fi networking advances which go beyond simple co-ordination. This brings in the notion of interworking with other Wi-Fi networks and how roaming to non-Wi-Fi networks can be achieved. Interworking and roaming methods under development today also include elements of co-ordination, which may be managed at a higher level than before.

2.2 Co-ordination methods

In the early days of Wi-Fi, the impetus was to develop a network without centralised control. Thus the medium access control (MAC) was designed to operate in a distributed manner in Wi-Fi networks. In other words the stations themselves controlled access to the medium. This is an easier approach then organising centralised co-ordination and leads to more flexible deployment, particularly for end users. IEEE 802.11 has been nomadically seamless in a single LAN segment from inception. In this way home or small office WLANs may operate multiple APs using a single common SSID/key combination. Clients can roam and authenticate without user intervention – but, nonetheless, the communications sessions may be interrupted for the order of seconds when changing AP. In other words, roaming authentication is seamless for the user, but seamless session mobility may not be offered to the application.

2.2.1 IEEE 802.11 extensions

In home deployments, the decentralised approach is still favoured today, but enterprise deployment of Wi-Fi has taken a different turn. Companies such as Cisco have driven IEEE 802.11 standards such that stations may become aware of their environment via measurements, are able to support handovers in a quicker, more seamless way, enable remote configuration of stations and perform all these functions securely. The ensuing working groups were 802.11k, 11r, 11v and 11w respectively[3].

11k covers measurements and 11v includes remote configuration; 11r for fast handover and 11w for management security are also relevant. We review each in turn.

IEEE 802.11k

The 802.11k working group specified a means to measure Wi-Fi radio characteristics and data that impact network performance. Specific functions include monitoring of AP throughput, channel selection, signal strength management and optimal AP selection. The standard effectively enables a user's device to select an optimal AP based on the current usage level in terms of active subscribers and overall data traffic. It does not allow the network to make the selection. Moreover, selection is influenced by the device's connection manager software, which is proprietary and varies in precise operation from device to device.

Having been concluded around 2005, 802.11k has been adopted quite widely by AP manufacturers. The standard is increasingly being included as standard in client devices, for example the latest version of Apple's iOS 6 running on iPhones and iPads supports the standard.

IEEE 802.11v

Whereas 802.11k is primarily about taking measurements to inform local decisions, 11v fills in a major gap by allowing use to be made of those measurements in order to enable centralised remote configuration of client device parameters. For example a client device can be directed to attach to any AP chosen by the network controller. This was a major change to the way 802.11 networks could operate.

Such control could be used to balance load in the network in a dynamic way, if a suitable management entity were also involved. For example, users could be directed to less well used access points, depending on the total dynamic network traffic and dynamic per-user traffic.

802.11v was ratified in February 2011. The standard also covers much broader functional areas, including power saving, location services and timing. It is important to appreciate that these other functions may be of greater general interest than the network management aspect. To our knowledge, overall adoption of 11v is low, although it was recently recommended by the GSMA for end of session signalling as part of a minimum Wi-Fi feature set[4], and its proxy-ARP[5] function is an option for future Hotspot 2.0 APs (see section 2.3.1).

---

[3] All have been superseded by incorporation into the IEEE 802.11 - 2012 standard, but we continue to discuss them separately for clarity.

[4] "Recommendations for Minimal Wi-Fi Capabilities of Terminals", GSMA document TS.22, June 2012.

IEEE 802.11r

As stated above, 802.11 has always allowed roaming within a single LAN segment. Although this was seamless from an authentication point of view, it introduced a connection drop while the client disconnected from one AP and associated with the next. This made it suitable for the original intention of nomadic operation, but unsuitable for more demanding applications, such as VoIP. 802.11r reduces the handover time and thus enables fast seamless roaming between APs for real time applications such as VoIP.

IEEE 802.11w

Previously, management frames were sent ‘in the clear’, meaning that malicious intervention was possible. 11w closes this avenue of attack and helps ensure the reliability required by real time services.

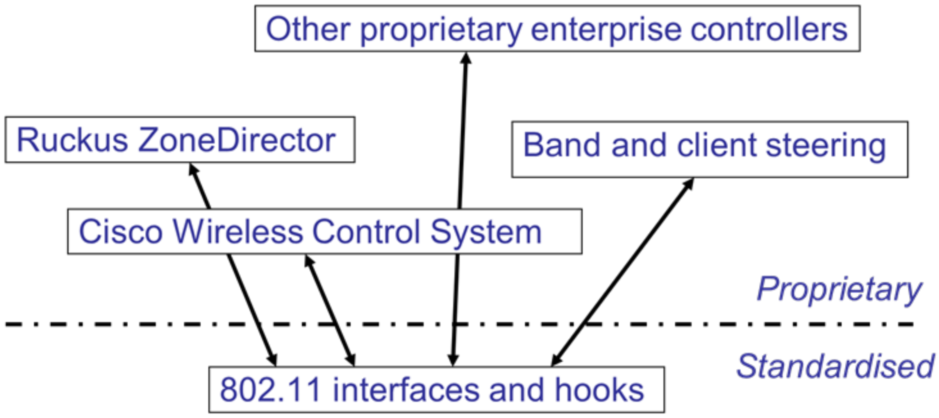
2.2.2 Enterprise network management

The amendments to 802.11 discussed above (11k, r, v and w) were driven principally by the enterprise communications sector. These extensions are however merely hooks to the lower level functions; in order to achieve a complete network management, controllers are needed in addition. These have been developed as proprietary network elements. Managed networks may be closed schemes where only a single manufacturer’s devices must be used, or a restricted range of accredited devices must be used in the network.

In other words, while the 802.11 extensions themselves may be standardised, they alone are not sufficient to create a managed network, since they define principally the physical layer and MAC level functions and interfaces. A network management entity must sit above these interfaces and provide the control function. It is this management which has been developed in a proprietary manner. We illustrate this in Figure 2-1 which shows example of commercial controllers, plus commonly used individual techniques of band and client steering, which we discus below.

[5] Simplistically, Address Resolution Protocol is used to ‘keep track’ of devices attached to an AP. Proxy-ARP is a modification to avoid broadcast events which may compromise security in some applications.

Figure 2-1 802.11 network management components.



2.2.3 Examples of proprietary techniques to improve network performance

Although the full details of how proprietary network management is carried out are not publicly available, there are a number of common techniques which may be employed.

Band steering

This entails pushing enabled users to 5 GHz where it is known that a client has a dual radio (2.4 and 5 GHz). This can be achieved by an AP listening to connection requests on both bands to identify dual radio clients and then simply refusing the 2.4 GHz connection.

Client Steering

Any AP can steer clients away by refusing to accept connections. When and why connections are refused is defined by proprietary network management policies.

Active channel selection

A relatively recent advance is active channel selection, in order to select less congested RF channels. This may be performed by individual APs, such as the BT Home Hub 3, or by a network controller such as in the Ruckus ChannelFly approach[6]. The ChannelFly approach does not constrain itself to the well-known independent channels 1, 6 and 11 at 2.4 GHz; rather it will measure all channels from time to time and select the ones which perform best, even if these are not channels 1, 6 or 11.

Air interface restrictions

A significant gain in throughput may be achieved by restricting access for less efficient legacy devices, notably 802.11b. In our interviews, some WMAN operators reported that they were considering enabling this restriction.

[6] See www.ruckus.com

Smart antennas /beam steering

Beyond simple steering of multiple omnidirectional antenna patterns by controlling differential phase, also known as ‘chip beamforming’, there exists the possibility to add more complex adaptive antennas to any 802.11 system.

Figure 2-2 Techniques for dense networks, including beam forming methods

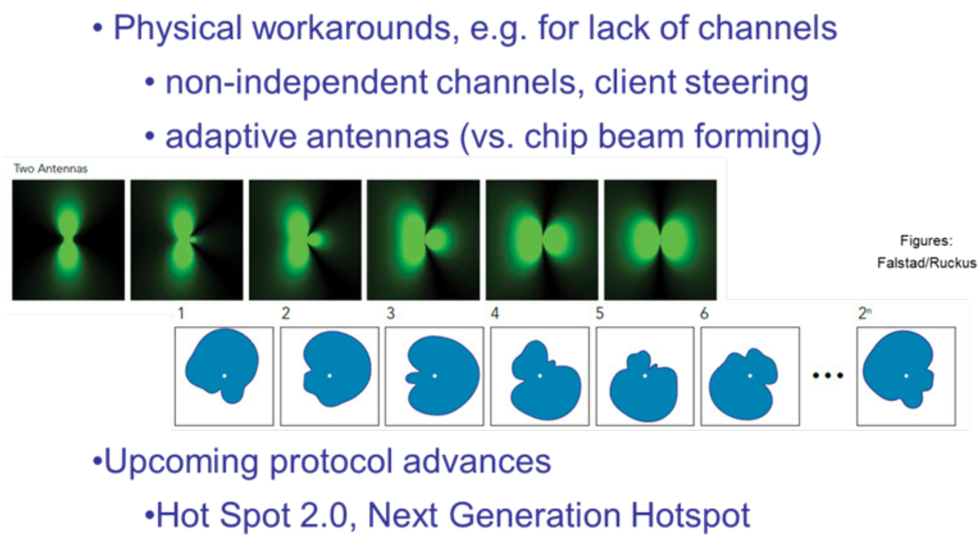


Figure 2-2 shows a series of antenna patterns resulting from chip beamforming in the green series of plots, based on feeding two omnidirectional antennas with varying phase difference. While it is clear that the beam is steered, the lobes are rather broad and often extend as far behind the antennas as they do in front. A more effective implementation of steering is shown in the series of blue figures where a more complex array of non-omnidirectional antennas is fed with variable signal phases. It can be seen that the main lobe can be steered as before, but the back lobe is much reduced. This increased front to back ratio, or directivity, is what enables a wanted signal to be maximised, while unwanted signals (which are assumed to be in other directions) are minimised.

2.2.4 The market for proprietary Wi-Fi management

The enterprise wireless LAN market represents about half of the total WLAN market. Enterprise WLAN revenues are expected to be around $5 billion by 2016[7]. This represents a doubling in market size since 2011. Cisco is the long established clear market leader, followed by Aruba, HP, Motorola and others. In the enterprise sector, the BYOD (bring your own device) effect is driving the need to upgrade; consumer video is the driver in the home and the advent of 802.11ac is driving both sectors.

[7] See, for example, Dell’Oro Group Wireless LAN 5-year forecast, http://www.delloro.com/products-and-services/wireless-lan

2.2.5 Limitations of co-ordination methods

The co-ordination methods described above suffer some limitations, depending especially upon the environment in which they are deployed. This is to be expected since they were primarily developed for the enterprise sector. There are two key areas where limitations may expect to be encountered, firstly in deployments outside the enterprise and secondly where large scale networking is under consideration, which may be summarised as follows

- A dependence on client device firmware supporting 802.11 extensions is reasonable in the enterprise – where client device type may be restricted in a closed enterprise system, but this is not realistic in the metro area. In fact it is becoming less feasible in the enterprise, due to the BYOD[8] effect. While it may be technically possible to upgrade user devices by firmware, low end devices tend not to be well maintained by either manufacturer or user. This creates a legacy device performance problem in the enterprise, and may equally be expected to hinder the wider take up of 802.11 extensions in the metro and consumer realms.
- Co-ordination methods tend to be simple, rules based approaches, often working close to the physical layer. The scalability of such an approach may be open to question. It would be preferable to have a higher level, scalable, policy based approach for large networks.

Recent developments in interworking and roaming have begun to address both these limitations, as we describe next. However, simple co-ordination methods may remain most appropriate for small Wi-Fi networks, such as home networks[9].

2.3 Interworking and roaming methods

Moving up in scale beyond SOHO or enterprise WLANs and towards WMANs deployed over larger areas, there naturally arises a need for more scalable network management approaches, which can cope not only with the larger network size, but also with interworking with and roaming to other wireless networks.

There are a number of initiatives in this area

- Hotspot 2.0, from the Wi-Fi Alliance;
- Access Network Discovery and Selection Function (ANDSF), from 3GPP;
- Next Generation Hotspot (NGH) from the Wireless Broadband Alliance.

In the following sections we summarise each in turn.

[8] Bring Your own Device.

[9] But see Section 2.3.6 with respect to the opportunity for expanding Next Generation Hotspot into homes, especially where the same provider is used for Fixed and Cellular service (or a roaming agreement exists). This raises an issue of user choice.

2.3.1 Hotspot 2.0

Hotspot 2.0 from the Wi-Fi Alliance (WFA) is designed to simplify ease of connection from the user's point of view and to ensure security of transmitted data. The user will no longer be presented with a list of SSIDs, and the network will see Wi-Fi access as trusted. Simply put, it aims to bring the seamless cellular experience to Wi-Fi users. From the network point of view the user connection is authenticated and secure, in other words it can be trusted – which is especially important to facilitate interworking with a cellular network core. This is a major change for Wi-Fi networks, which have traditionally been considered to be untrusted by cellular core networks. Hotspot 2.0, which is certified by the WFA under the name PassPoint™, draws heavily from 802.11u for network discovery in a pre-association phase and from 802.1X's extensible authentication protocol (EAP) plus 802.11i encryption. Security is WPA2-Enterprise, as certified by the Wi-Fi Alliance; lesser security is not permitted by Hotspot 2.0. The Hotpot 2.0 specification is closed to the public, but the key features have been advertised by the WFA and been reviewed in numerous publications[10]. Figure 2-3 shows the discovery and authentication parts of Hotspot 2.0. Payload security by WPA2-Enterprise is already enabled by 802.11, via the older 802.11i amendment.

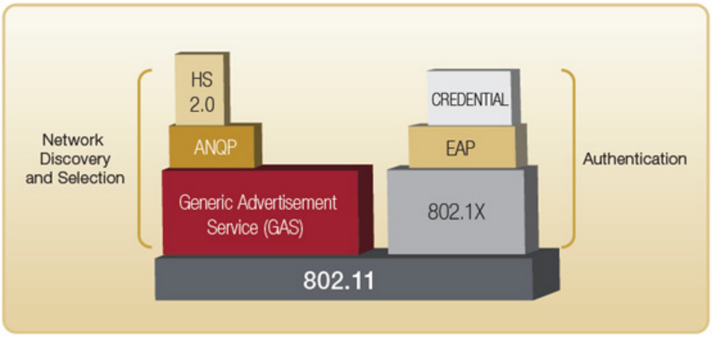


Figure 2-3 Hotspot 2.0 pre-association discovery and secure authentication[11]

Pre-authentication discovery and selection is a major change for Wi-Fi and it means that the SSID will no longer be the prime means to identify whether a particular AP is capable of offering a service to a user. This will be welcomed by users and network operators alike. From the user's point of view, seamless authentication will become the norm and encountering a discouragingly long and cryptic list of SSIDs will become a thing of the past. From the network operator's point of view, there will be efficiency advantages. SSID beacons consume bandwidth as they are network management frames - in other words they represent overhead. Around six SSIDs is often a practical limit, as beacons are sent every 100msec, at the lowest supported

[10] Such as "Wi-Fi Roaming - Building on ANDSF and Hotspot2.0", white paper from Alcatel and BT, 2012, or "Achieving carrier-grade Wi-Fi in the 3GPP world", Ericsson Review, 2012.

[11] Figure from "Integrating Wi-Fi RANs into the Mobile Packet Core", Ruckus white paper, 2013.

data rate[12]. HotSpot 2.0 enables the number of SSIDs which need to be transmitted in a multi-operator-agreement environment to be reduced. Legacy devices not using Hotspot 2.0 may still be able to connect via an SSID, if the operator's policy permits it.

Hotspot 2.0's Access Network Query Protocol (ANQP) and General Advertisement Service (GAS) will be able to obtain a number of Information Elements (IE) relating to network capabilities from an AP, for use in seamless and secure Wi-Fi logon. There will also be hooks for cellular operators, such as cellular network information and consortium lists (of Wi-Fi – cellular roaming agreements), plus of course authentication options. For example, this would enable a SIM enabled Wi-Fi device to preferentially associate with an AP operated by the cellular service provider. However it can be overridden by the user so that, for example, a private home or office Wi-Fi network may be used instead.

Additionally, network performance metrics may also available from the AP in the pre-association phase. These can include WAN metrics such Internet connection status (up/down speed, walled garden) or AP load (up/down/at capacity). This will allow an intelligent choice of AP to be made, where a range of suitable APs is present. For example where an AP is indicates it is operating at capacity, then association is unlikely to result in a high quality connection. This is essentially an implementation of pre-association admission control by the network in order to ensure an excess load condition is avoided, before it occurs. In a similar pre-emptive way a device can also decide whether prospective AP/Internet capacity is suitable for the application in use or about to be used (e.g. video streaming).

The Hotspot 2.0 specification supports four standard authentication protocols commonly deployed in the industry

- EAP-SIM – for devices with SIM credentials;
- EAP-AKA – for devices with USIM credentials;
- EAP-TLS – for use with a trusted root certificate;
- EAP-TTLS with MSCHAPv2 – for username-password credentials.

This range caters for Wi-Fi devices with and without SIM cards. Operator policies and instant online sign-up will be a feature of phase 2 of Hotspot 2.0 later in 2013. Secure online signup will be especially important for those devices which have no pre-existing account and cannot authenticate by SIM card (e.g. because they are Wi-Fi only, like the majority of tablets). Policies will provide a guide for which network a device should connect to. This will vary with location, but could also vary

[12] This is an industry rule of thumb. Briefly the overhead depends on the number of SSIDs, but also the lowest rate supported by an AP as the beacon is sent at this rate. To reduce overhead, the number of SSIDs can be reduced or the lowest supported rate can be increased, at the expense of potentially rejecting some legacy devices. With 6 SSIDs and 802.11b rates enabled, the over head can approach 25%. Clearly a lower overhead is better and a few per cent is a reasonable aim.

with time of day or device traffic needs, for example. However, policies are pre-provisioned and are stored on the device. The implication is that they cannot react in real-time to any revised guidance from the network.

A corollary of the authentication approach used in Hotspot 2.0 is that legacy open access and captive portals will not be usable, due to an insufficient level of trust. However, it legacy access schemes are assigned to an alternate SSID, then they may be operated in parallel with, but independently from, Hotspot 2.0. On the other hand if legacy access is already via WPA-Enterprise, then integration into Hotspot 2.0 will be straightforward.

The Wi-Fi Alliance is already certifying Hotspot 2.0 phase 1 devices.

2.3.2 ANDSF

The Access Network Discovery and Selection Function (ANDSF) from the 3GPP is intended to extend a degree of control by mobile operators over which Wi-Fi networks a device will preferentially attach to. It is noteworthy that, while ANDSF will allow operator policies (which are downloaded to a device) to be revised to a degree, it should not be considered to be dynamic in the normal networking sense. Therefore ANDSF is not intended to perform real time network selection, based on prevailing network performance.

We note that ANDSF may conflict with the device connection manger and this is currently a source of uncertainty for the future prospects of ANDSF, see Section 2.3.6.

2.3.3 NGH

Next Generation Hotspot from the Wireless Broadband Alliance is a collection of initiatives including a program of testing the interoperability of WFA PassPoint™ certified equipment with carriers' back-ends. One reason this is important is that Hotspot 2.0 works in an abstracted, pre-authentication mode to identify service providers, whereas ANDSF works directly with SSIDs to identify service providers. Work to integrate Hotspot 2.0 and ANDSF policy operation is on-going.

Any aims for such integration are likely to include a more dynamic network selection process based on cellular versus Wi-Fi performance in near real time. For example, an example of an obvious situation to be avoided is offloading from cellular at 3Mb/s to Wi-Fi at 500kb/s. It is conceivable that proprietary schemes to control such real-time hand-off issues will be created in the market in advance of any industry wide specifications.

2.3.4 Degrees of seamlessness

Hotspot 2.0 addresses seamless authentication. It does not necessarily offer a seamless approach to IP session mobility. But an important case where session mobility will be offered is where a cellular connection is offloaded to a Wi-Fi connection which is routed through the cellar core (such that the mobility anchor is maintained). Where hand-off is to the Internet directly, then session mobility is less likely to be available and the device will may acquire a new IP addresses, via which the session may need to resume after an associated delay.

In fact there are a number of methods to ensure IP session mobility. In brief these consist of bespoke schemes within 3GPP and open schemes from the IETF. There has been a long debate in the industry about which is better. Such arguments generally run along the lines of questioning why the 3GPP needs to re-invent the wheel, when IETF standards can perform the functions on the one hand, versus 3GPP proponents suggesting that their tight integration of dedicated functionality can deliver better results (in both technical and business senses).

In both 3GPP and IETF cases there are several options for providing for fully seamless hand-off. In the IETF case these include several Mobile IP variants and from 3GPP there are a number of proprietary approaches, all of which are well-proven. All may be spilt into device or network based mobility, such as DSMIP or IWAN for devices versus PMIP or GTP for the network[13]. A major consideration is that the introduction of network based mobility approach does not require changes to the user's device - and requiring such changes has been a reason for poor uptake in the past.

As a point of comparison, the normal handoff method today is not seamless as it does not normally maintain IP address as it does not transit the cellular core network[14]. The advantage is primarily simplicity in that it requires no mobility or tunnelling protocol on the device; the disadvantages include a loss of control from the cellular operators' perspective and the absence of an opportunity of per flow IP control which could be important to user applications. In the future the simple, non-seamless type of hand-off may remain the preferred way to connect to home or small office networks, with the developing IP mobility approaches more suited for WMAN or other managed network hand-offs.

In terms of developing a perspective on the degrees of seamlessness issue, we expect that authentication seamlessness is likely to have by far the largest effect on the uptake of Wi-Fi offload for all users, as it removes a key barrier. The reason that hotspot usage stands at a relatively low percentage has been directly attributed to this usability barrier. On the other hand, session seamlessness is likely to be important to only a relatively smaller proportion of users, at least initially.

2.3.5 Alternative roaming approaches

An alternative way to provide public access to Wi-F is to use a co-operative approach whereby access point owners agree to allow each other to access their connections. Such an arrangement can be facilitated either by the user's host network (broadband provider) or by using specially configured routers that are able

[13] Dual Stack Mobile IP, Interworking WAN, Proxy Mobile IP and GPRS Tunnelling Protocol respectively.

[14] 3GPP refers to this as Non-seamless WLAN off-loading (NSWO).

to identify users who are party to the agreement and carry traffic from visiting users separately from the home user's own traffic.

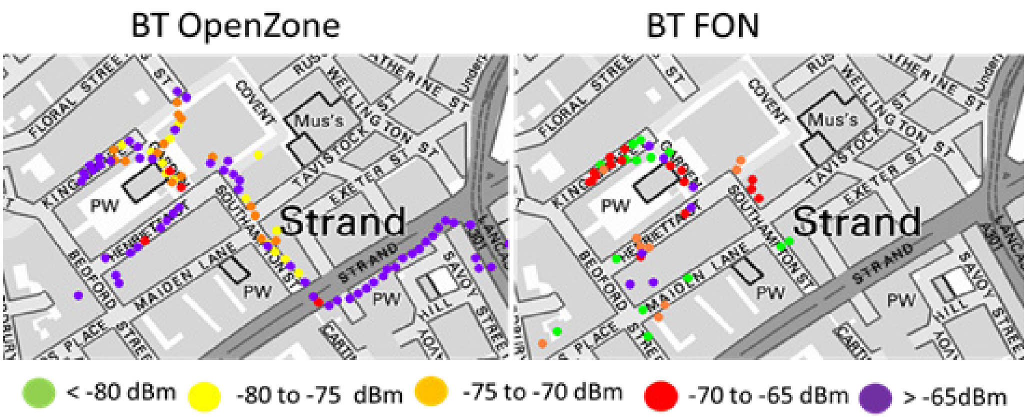
The main instigator of such services in Europe has been the Spanish company FON, has established agreements with a number of European broadband providers to enable their subscribers to benefit from such a sharing arrangement. In the UK, FON has partnered with BT to enable BT Broadband subscribers and selected FON roaming partners to gain access to over 4 million BT Broadband subscriber access points.

FON's approach works by setting up a separate Wi-Fi connection from the router – this uses the same radio signal and channel as the user's own private connection but comprises a second parallel data link with a FON-specific service set identifier (SSID) which is separated from the user's private connection by a firewall. The home user's private traffic is prioritised and that connections via the FON signal should not therefore impact on the performance of the home broadband connection.

FON is a member of the Wi-Fi Alliance, and plans to adopt the latest Wi-Fi Alliance certified Passpoint™ and IEEE 802.11u protocols to enable automatic detection and authentication onto FON hotspots.

Whilst this approach is clearly attractive in terms of the number of public access points that can be made available, it is questionable how attractive this is as an alternative to a dedicated WMAN, since the FON signals provide relatively little outdoor coverage. To illustrate this, the figure below compares the detected signal level from BT Wi-Fi Openzone hotspots (many of which are located outdoors) and BT FON access points at various locations around Covent Garden. It can be seen that the extent of coverage from the Openzone hotspots is far greater and that the detected signal is in most cases considerably higher.

Figure 2-4 Comparison of BT Openzone and BT FON coverage at street level at selected locations in the Covent Garden area of London



source: Aegis Systems

The Swedish company AnyFi[15] has developed a similar approach in which modified routers are used to provide users with access via each others networks. However, access is obtained by entering the credentials for the user's own home network. When a visiting user's device detects an AnyFi router, the Wi-Fi authentication credentials are sent via the visited router to the device owner's home gateway, using secure tunnelling technology similar to that used in virtual private networks. The user's device therefore behaves as if it were on its home Wi-Fi network, and the same security measures are put in place as the customer uses at home, ensuring a secure Wi-Fi connection.

The downside of this is that network traffic is increased and most importantly, modified routers need to be employed. Therefore a key enabling element of AnyFi's business case is to persuade router manufacturers to incorporate the necessary modifications, and to have such routers deployed in a significant density in the market.

AnyFi is targeting its offerings at Internet service providers in a similar fashion to FON, although they do not as yet appear to have any commercial agreements in place.

2.3.6 Areas of uncertainty

There are two key areas of uncertainty related to the market penetration of the various interworking approaches. One is a relatively simple issue with respect to the means of identification of service providers, which currently differs between ANDSF and Hotspot 2.0. The other is a rather more challenging issue of empowering user choice with respect to service provider.

- Firstly there is a mismatch between the Hotspot 2.0 pre-authentication paradigm which dispenses with the need for SSIDs during network discovery, versus the continuing key role of SSIDs within ANDSF. However we understand this issue is already under study.
- Secondly the role of the device manufacturer, specifically the implementation of the connection manger, is presently undefined. To date, the choice of provider selection has been left to the implementation and user input. However, with an increasing choice of providers and a desire by competing operators to direct that choice, comes the dilemma of which network should be given priority, if any. The device manufacturer, who controls the connection manager, is likely to resist any perceived bias; this may cause resistance to ANDSF adoption in the market. The same issue should also help perpetuate free user choice.

We pick up these issues again in Section 2.4, under point 7.

[15] See www.anyfinetworks.com

2.3.7 Future direction

We suggest that a logical extension of the Hotspot 2.0 approach could be a move to wholesale provision of Wi-Fi as a Service, in other words a single network operator serving a number of service providers. This may also be driven by consolidation in the industry and would have the additional benefits of avoiding a land grab for Wi-Fi sites and reducing the congestion which can be caused by competing operators.

2.4 Implications for future spectrum efficiency

Having described the key components within the co-ordination and interworking categories, we can now examine their implications for future spectrum efficiency.

Potential spectrum efficiency implications due to **co-ordination** advances are as follows

1. 802.11k, r, v w. As these extensions were driven by enterprise networks using proprietary management schemes, the magnitude of the benefit in terms spectrum efficiency alone is hard to isolate. Associated benefits such as fast roaming for VoIP can be more important spectrum efficiency in Enterprise networks. Most relevant to the present study is that the 802.11 extensions principally make a network easier to co-ordinate, i.e. to plan and manage; this simply avoids unnecessary spectral inefficiencies which may be found in un-coordinated networks (such as residential Wi-Fi deployments, for example);

2. Adaptive Antenna modules. Such additional adaptive antenna arrays are used by some manufactures to provide beam steering and nulling. They represent a step beyond phase controlling the usual omnidirectional antennas as we showed in Figure 2-2. It is well accepted that beam steering towards a user, while nulling other users, can achieve a signal to noise advantage, which must translate into better spectral efficiency for that link. What is less in evidence is that such antennas will remain as advantageous in very dense deployments where a number of competing operators are vying to achieve coverage. Specifically, what is not yet sufficiently clear is whether adaptive antennas can successfully demonstrate an advantage, given that wanted and unwanted signals may lie in the same direction – a situation more likely in a dense, mixed operator environment;

3. Load balancing via simple steering, e.g. via MAC. Simple steering may include client or band steering. In the first case a client may be refused access to an AP which is busy; in the second case a client which has a dual radio may be refused access at 2.4 GHz, but allowed into the presently quieter 5 GHz band. Both types of steering are presently routinely achieved via proprietary AP behaviour. Both improve technical spectrum efficiency as they help even out the load on the available pool of spectrum. Nonetheless we caution that network load balancing in any form is really concerned with

avoiding inefficient use of resource rather than improving the best use of the resource;

4. Guided channel selection. One popular residential AP will search each of channels 1, 6 and 11 up to three times per 24 hours and will select the channel exhibiting best CIR. One popular outdoor AP will monitor all channels and select the best channel (not restricted to 1, 6, and 11) over an unpublished time period. The improvement offered by the residential device has not been characterised to our knowledge. From our industry interviews we have found that some operators have reported significant capacity improvements when using APs capable of selecting non-standard channels. Our concern with these approaches in general is what may happen when, rather than being the minority approach today, they could be the majority approach in future. If all APs are regularly trying to optimise their channel selection via a similar but un-coordinated algorithm, then one possible outcome is a regular churn of channel selections, but to no long term advantage. In other words we question the scalability of this approach, at least unless centrally co-ordinated. The possibility for central co-ordination is much less in a residential environment than a managed WMAN, so this is where we see the greatest uncertainty.

It is interesting to note that three of the four points above are related to no more than avoiding inefficient use of spectral resource. Of course this is to be expected from co-ordination efforts; but equally apparent is that revolutionary gains in performance should not be anticipated. Moreover performance gains should be expected to vary with the network load distribution created by the users. We evaluate this last point via scenario analysis in Chapter 5.

Potential spectrum efficiency implications due to **interworking and roaming** advances are as follows

5. Reduction of broadcast overhead via Hotspot 2.0 pre-association discovery. Wi-Fi broadcasts beacons at the lowest configured rate many times a second. Hotspot 2.0 may enable the associated overhead to be reduced, via a reduction in the number of SSIDs at a given AP. Furthermore, a client may discover valid APs on the local network before associating with any AP, so further reducing management overhead. The advantage from this in terms of spectrum efficiency arises from the reduction in management overhead and is not likely to exceed 10% in a typical network, depending upon actual configuration. However this advantage in efficiency is likely to be dwarfed by the increase in the number of users once Hotspot 2.0 makes Wi-Fi logon a seamless experience for the user.

6. Load balancing and offloading – via interworking protocols, e.g. Hotspot 2.0, ANDSF. Both protocols are intended to steer clients efficiently to the most suitable network. This will be a network with which the client has a usage agreement, or can sign up on the spot (Hotspot 2.0 release 2). The client will

also be able to obtain network load information which the client connection manager (in the device, see below) may use to select an AP with suitable radio load and Internet connectivity. The user will nonetheless be able to overrule AP selection. As with load balancing by simple client steering (see 3 above), load balancing by interworking protocols aims to reduce allocation inefficiencies in the system, rather than create revolutionary capacity improvements.

7. Connection manger effectiveness and uniformity. Since Wi-Fi was designed from the outset to operate with a distributed networking protocol, it should come as no surprise that the behaviour of Wi-Fi with respect to handovers etc. is device specific. Whoever writes the device software stack is in control of device behaviour at the detail level. Sometimes this leads to inconsistencies such as sticky clients, which remain associated with a chosen AP regardless of the fact that they may be within easy range of better AP. (Industry feedback tells us that laptops tend not to have overly sticky clients, but smartphones and dongles can exhibit an unhelpful stickiness at times). It is also the job of the connection manger to decide when to connect to cellular or Wi-Fi. At the moment this aspect is still predominantly user driven. The cellular operators would like to be more in control over this process, so that they may hand over their users to the operators' preferred non-cellular networks which may continue to transit the packet core and thus remain visible to the operator, for example. On the other hand, device vendors may be reluctant to accept such polices from the cellular operator. Vendors might reasonably ask who owns the end user – cellular or Wi-Fi. This might be a barrier to ANDSF adoption in the market. Moves to define common connection manger operation are being instigated within the Open Mobile alliance (OMA) and the IETF.

It is noted that in all cases, the magnitude of the potential spectral efficiency improvements are relatively modest, especially when compared against the likely magnitude of the expected traffic growth rate in the future. Furthermore, at the risk of labouring the point, it is one thing to make a given network operate at optimum efficiency, but quite another to make sure such a network is dimensioned appropriately for the traffic and traffic growth expected. In the first case modest and diminishing returns might reasonably be expected and in the latter case an increase in capacity of orders of magnitude might be required well into the future.

The applicability of all the effects listed above may be expected to vary by deployment type. We characterise this for four types

- WMAN (outdoor public networks, operator managed);
- Hotspots (indoor public networks, operator managed,);
- Enterprise (private indoor networks, centrally managed);

- Residential or small office (private indoor networks, unmanaged possible FON extensions).

We can summarise the applicability of the potential spectrum efficiency improvements for each deployment type in Table 2-1

Table 2-1 Applicability of efficiency approach versus deployment type

Approach>	1	2	3	4	5	6	7
WMAN		X	X	X	X	X	X
Hotspots		X	X	X	X	X	X
Enterprise	X	X	X				X
Residential		X		X			X

It is interesting to note that the two features applicable to all types of installation are firstly adaptive antennas, since they may be added independently for the benefit of any traffic and secondly the connection manger software within the device, as this determines which network the device will connect to, when it will roam and whether user preference may take precedence. We discuss the anticipated performance of these deployment types within the three main scenarios in Chapter 5..

Finally, we note that a new version of Wi-Fi has recently been introduced (802.11ac) and we next summarise the likely implications for spectrum usage.

2.5 IEEE 802.11ac

Quotient recently investigated the likely future technologies to be used in licence exempt bands, including the latest, 5th generation, of Wi-Fi[16]. This 802.11ac standard is now in sponsor ballot and may be released later this year. It is quite common for manufacturers to release draft-standard products, such as ‘draft-n’ before the 802.11n a specification was formally released. Hence we may see ‘draft-ac’ products in the marketplace now and for a time. In fact future products are likely to be 11acn, since unlike 11n, 11ac operates at 5 GHz only.

A key advance for 11ac is higher speed and one of the ways this is achieved is via wider channels of 80 and 160 MHz. However, unlike 11n, a fall back to narrower channels is mandated in the 11ac draft standard, such that fairness of medium access is offered to legacy 20 and 40 MHz channel devices. This is referred to as ‘dynamic bandwidth’ in 802.11ac Draft 5.0 and is a key change to how 802.11 operates.

A corollary of this is that we should not expect the new, wider channels to ‘crowd out’ legacy devices by ‘filling up’ the band. On the other hand, if wider channels are

[16] “Technologies and approaches for meeting the demand for wireless data using licence exempt spectrum to 2022”, Quotient Associates for Ofcom, January 2013, (to be published).

to be used successfully, then sufficient free bandwidth needs to be available, such that contention and hence fall back may be avoided. In Quotient's earlier work for Ofcom, this was seen as a key driver for expanding the amount of contiguous spectrum available at 5GHz for Wi-Fi.

2.6 IEEE 802.11 High Efficiency Study Group proposal

At the time of writing this report, a proposal had just been put forward to create a High Efficiency study group within 802.11, to address the issues of high density WLAN deployments. There are few details on this since the IEEE Project Authorisation Request has not yet been submitted. However, it is worthwhile to consider the likely drivers of such a move. We provide the following discussion as an introduction.

It is very well known firstly that too many active clients can slow down a Wi-Fi Network, and secondly that having too many SSIDs leads to a bigger overhead, thus also slowing down the network. The first issue results partly from the basic CSMA operation and was the reason why, in the late eighties, Ethernet moved from shared medium to switched. In practical Wi-Fi, the situation is made much worse by the practice of throttling the transmission rate when packets are dropped (adaptive rate selection). Today, Wi-Fi deployments continue to assume only a proportion of clients will be active, so side-stepping this problem. The second issue provides an impetus for AP manufacturers to limit the number of SSIDs that can be allocated by the installer. These problems are becoming more visible as higher density deployments are becoming more common outside the enterprise (where walled gardens mask the issues).

It is to tackle these problems that IEEE 802.11 is proposing the new High Efficiency study group. However, it is not clear at the present time to what degree this will address multi-operator environments, which introduce a complication beyond a homogeneous high density deployment, due to different operator domains. Multi-operator Wi-Fi has recently been the focus of university research[17]. Findings include that there are situations where competing WMAN providers (say, BT and the Cloud) will not be able to optimise their network in the presence of the other network. The proposed solution is inter-network co-operation (e.g. the Cloud and BT co-manage their networks), which clearly has business implications. It may be that in real world deployments, operators will not be able to differentiate this issue from other optimisation issues and will simply address the problem in a pragmatic way, by siting/moving APs based on RF analysis, at least in the short term.

We note that the advent of a limited number of wholesale operators in the market would offer a better opportunity for inter-network co-operation. A further driver for

[17] See, for example, "Network Cooperation for Client-AP Association Optimization", Baid et al, 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), May 2012.

wholesale operators arises from the limitations of the ‘land-grab’ for Wi-Fi sites in dense built environments (e.g. Virgin on London Underground).

3 CURRENT STATUS OF WMAN DEPLOYMENTS IN THE UK AND ELSEWHERE

3.1 Introduction

In this chapter we review the extent to which WMANs have been deployed within the UK and elsewhere. We have identified a number of existing and planned deployments of Wi-Fi WMAN networks in the UK, including:

- **Virgin Media:** indoor network serving London Underground stations and outdoor network serving Leeds and Bradford city centres. Further outdoor networks planned.
- **BskyB / The Cloud:** outdoor network serving the City of London. Also operates a large network of indoor Wi-Fi hotspots.
- **Telefonica / O2:** outdoor networks serving various locations in central London. Also operates a large network of indoor Wi-Fi hotspots.
- **BT Wi-Fi:** outdoor networks serving several city centre locations. Also operates a large network of indoor Wi-Fi hotspots and over 4 million shared residential access points operated in conjunction with Swedish company FON.
- **Global Reach:** operates an outdoor network along the River Thames in London that provides access to BT Wi-Fi subscribers and river users.
- **Bristol:** joint venture between Bristol City Council and Bristol University

Other examples of Wi-Fi MANs include an extensive municipal network in Barcelona, a large number of smaller scale networks in Spain and a number of FON-supported shared access networks in other European countries. Outdoor networks have also been widely implemented in the US and many other countries around the world, although in some cases networks have closed due to funding difficulties (in the case of some municipal networks) and concern from other operators about unfair competition.

There have also been some failed WMAN initiatives in the UK. For example, the London Borough of Islington established a "technology mile", extending for a distance of 4 km from the Angel along Upper Street and Holloway Road, along which free public Wi-Fi was provided in partnership with CItyspace. Funding cuts led to the suspension of the service in 2011. A plan by Swindon council to provide free Wi-Fi via lamp posts for the whole of the town in 2010 was also thwarted due to funding problems and difficulties finding a private sponsor[18]

[18] See http://www.bbc.co.uk/news/magazine-14835059

In the following sections we describe in more detail the main established WMAN deployments in the UK and Europe, based on interviews held with some of the networks (Virgin Media, BskyB and O2) and on our own research.

3.2 WMAN deployments in the UK

3.2.1 Virgin Media

Although it is the second largest residential fixed broadband provider in the UK, Virgin Media has relatively modest ambitions with regard to public Wi-Fi and is more focussed on developing small cell solutions for licensed mobile network operators. The company has recently developed a concept known as Small Cells as a Service, which involves working alongside local municipalities to develop outdoor urban small cell networks using street furniture to support both Wi-Fi and 4G (LTE) femtocells. By partnering with the local authorities, Virgin Media gains access to the sites and power facilities necessary to roll out the small cell network. In return, Virgin is required to provide fee Wi-Fi access within the terms specified by the local authority.

Virgin currently operates two relatively large scale public Wi-Fi networks, one serving stations on the London Underground and the other an outdoor network covering the cities of Leeds and Bradford. The networks are managed on Virgin’s behalf by Global Reach (see below) and are based on dual band access points. However, according to Virgin only the 2.4 GHz band is currently used, although the higher band is used to provide meshing of access points in the outdoor networks. This approach probably makes sense on the London Underground, since by its nature this is a relatively benign radio environment, but is perhaps more questionable for the outdoor networks where interference and contention come into play.

Access to the London Underground network is limited to subscribers of Virgin Media and various partners, which include three of the four UK mobile networks (Vodafone, O2 and Everything Everywhere). Virgin describes these arrangements as wholesale agreements rather than roaming, in that the mobile customers must first pre-register with their network, rather than access being allowed automatically e.g. via SIM authentication. Access to the outdoor networks is free to all users.

With the exception of the London Underground (where Virgin is a sole provider of Wi-Fi services and can market these on a wholesale basis to other networks), Virgin does not consider public Wi-Fi as a viable business in its own right. Rather, Wi-Fi is seen as an innovation platform to prove the concept of small cell networks, which if successful will be extended to wholesale provision of backhaul and site access for mobile operators with their own licensed spectrum.

3.2.2 The Cloud (BskyB)

The Cloud is currently the biggest public Wi-Fi hotspot operator in the UK, with over 16,000 active hotspots. The company also operates a meshed outdoor WMAN in the City of London. The network is dual band throughout with automatic steering of dual band clients to the 5 GHz band. 5 GHz is also used for meshing purposes in the outdoor network, along with some 5.8 GHz light licensed spectrum. The entire network uses Ruckus infrastructure with dynamic channel selection and beam forming to maximise capacity.

The Cloud places a strong emphasis on providing high capacity for video streaming. This is largely aimed at enabling BskyB TV subscribers to access video content on the move (for which an additional subscription is payable), since the mobile networks are not considered capable of delivering video with sufficient quality. Peak usage tends to be weekend evenings, when some users can download hundreds of MB per session.

The network is free to access for up to two devices per customer, subject to pre-registration. Roaming agreements have been reached with some overseas mobile operators (most notably AT&T in the US, whose subscribers generate significant traffic on the network).

3.2.3 O2 Wi-Fi (Telefonica)

O2 Wi-Fi is the second largest public Wi-Fi hotspot operator in the UK, with approximately 7,000 active hotspots. The company also operates outdoor Wi-Fi networks in parts of central London. Most hot spots and all outdoor access points are dual band.

Traffic levels to date are relatively low at most hotspots (we were told an average throughput of around 128 kbps per site is typical), but significantly higher in the London outdoor networks, where traffic levels have been found to be six to seven times higher than the local traffic carried over O2’s cellular data network. Interestingly, since the outdoor network went live in 2012, there has been no reduction in the traffic carried locally over the cellular network, implying that the Wi-Fi traffic is incremental to that carried over the cellular network rather than off-loaded. This could, for example, be due to a large number of Wi-Fi only devices (e.g. tablet PCs) connecting to the network.

The network currently uses MAC authorisation of pre-registered devices. SIM-based authentication for O2 mobile subscribers is planned in the future. There are no roaming agreements currently and no immediate plans to deploy Passpoint™ or Hotspot 2.0, although many of the hotspots can be software upgraded to provide this.

A key part of O2 Wi-Fi’s business strategy is focussed on gathering and aggregation of customer profile data. Each time a customer visits a hot spot venue, the device automatically connects regardless of whether the network is used, and this can be used to generate valuable marketing data that can be sold back to the venues concerned, compensating for the lack of direct revenue from the Wi-Fi itself, which is freely available to all users subject to a one-time registration.

A further motivation for the outdoor networks was that these would in the future support licensed LTE small cells alongside Wi-Fi as part of O2's existing UK mobile network; however, this now appears less certain following the company's failure to acquire spectrum in the 2.6 GHz band (ideally suited to small cell deployment) in the recent UK spectrum auction. This may lead the company to place increased reliance on Wi-Fi to support network capacity, at least in the shorter term.

3.2.4 BT Wi-Fi

BT Wi-Fi operates over 4.5 million Wi-Fi hot spots in the UK. The majority of these are residential BT hotspots but there are also c. 300,000 BT Business Hub hotspots and c. 6,000 indoor hotspots in locations like cafes and hotels. BT also operates outdoor networks in twelve cities across the UK, referred to as wireless cities – these include Glasgow, Edinburgh, Newcastle, Leeds, Liverpool, Sheffield, Nottingham, Birmingham, Portsmouth, Bristol, Cardiff and London. The network in central London covers approximately 7 square miles in total. BT Wi-Fi also provides indoor hotspots at various locations in Germany, Ireland and Spain.

Although all hotspots now operate under the single BT Wi-Fi brand, there are two distinct approaches to providing service, namely the premium estate comprising of the cafes, hotels, shopping centres etc. plus the wireless city networks, and the shared community hub hotspots.

BT Wi-Fi is planning to rollout 802.1X across its premium estate in the near future which will support secure authentication including EAP-SIM and TTLS. BT already has roaming agreements with all of the UK mobile networks except Three. EAP-SIM authentication is already supported by BT's network but currently only works with Vodafone. One of the problems with SIM-based roaming has been limited support by client devices – for example Android smart phones prior to version 4 did not fully support EAP-SIM providing a very poor user experience on service provisioning and operation.

Roaming agreements are also in place with various overseas mobile networks and with other Wi-Fi networks. There are also wholesale agreements with other companies such as iPass, Boingo and Skype, the latter available through Skype Access which is a way of paying for short duration internet sessions.

Current technology supports automatic authentication but not seamless session transfer, which is standard in the vast majority of Wi-Fi operations globally. BT did not specify which standards they would expect to employ for seamless session mobility in the absence of an EPC (cellular core) connection[19]; this is under investigation with their cellular partners and within the standards bodies.

BT's hotspots currently use a number of SSIDs (e.g. BT Openzone, BT Wi-Fi, BT Wi-Fi with FON). Ideally BT would like to be able to dispense with SSIDs altogether

[19] When connected via a trusted network approach, e.g. via HotSpot 2.0, the mobility anchor is in the cellular core for both cellular and Wi-Fi.

and use automatic network discovery and authentication, but they will have to be retained for the foreseeable future to cater for legacy devices and because the alternative mechanisms such as PasspointTM are not yet fully mature.

BT would like to see roaming arrangement made more straightforward and this is another area of investigation that BT is undertaking with its WBA partners The Company's view is that Wi-Fi will always remain a complement to cellular rather than a substitute, the key benefit being the additional capacity and spectrum resource that it provides.

BT is active in various standards bodies including the WBA, GSMA and 3GPP. 802.11ac is of particular interest currently and BT is of the view that this could be used both for meshing / backhaul purposes and (primarily) in access networks, where it could provide both higher speeds and improved coverage, resulting in fewer access points being needed. Although BT procures hardware from external suppliers, firmware, software including its successful connectivity and other Wi-Fi apps and business modelling to use these developments are developed in house and are largely proprietary – this is considered an important area of competitive differentiation in the market.

Most of BT's existing access points run at 2.4 GHz but 5 GHz is progressively being rolled out across the premium estate and this process should be complete in the next 2-3 years. Where 5 GHz has been deployed it works well and there have been no problems associated with DFS in the band. Residential access points (Home Hub) are still single band (2.4 GHz) but this is likely to change in the near future. The Home Hub APs deploy a BT proprietary channel selection procedure but no information is publicly available on how effectively this performs in a high density environment.

BT supports the allocation of further Wi-Fi spectrum at 5 GHz in the future and that this should be exempt from licensing. The company has no strong view on whether specific technology requirements should apply to any new spectrum.

3.2.5 Global Reach

Global Reach is a UK based company that specialises in managed Wi-Fi solutions for the enterprise market but is also a network operator in its own right. The company has been working in partnership with other networks including Virgin Media and BT Openzone to support the rollout of outdoor WMANs. The company claims to be running one of the world's largest outdoor Wi-Fi mesh networks along the River Thames, providing 42km of coverage and offering a range of public and private services.

The network has recently been upgraded to incorporate Ruckus' ZoneFlex™ equipment with dual band beam forming technology. Access points are installed at main piers criss-crossing the Thames and also on board the 24-strong Thames Clipper ferry fleet. The company report that since the upgrade it has seen a significant improvement in signal strength and in the number of concurrent users and sessions that can be supported.

3.2.6 Bristol "BOpen" Network

The BOpen network is an open Wi-Fi network that is free for anyone to use. It is provided by Bristol City Council and is available at many locations across the city. The network comprises over 50 municipal hotspots in libraries, museums, care homes and public areas such as St Nicholas Market and parts of Ashton Court. In 2011 access was also provided to the University's 600 access points.

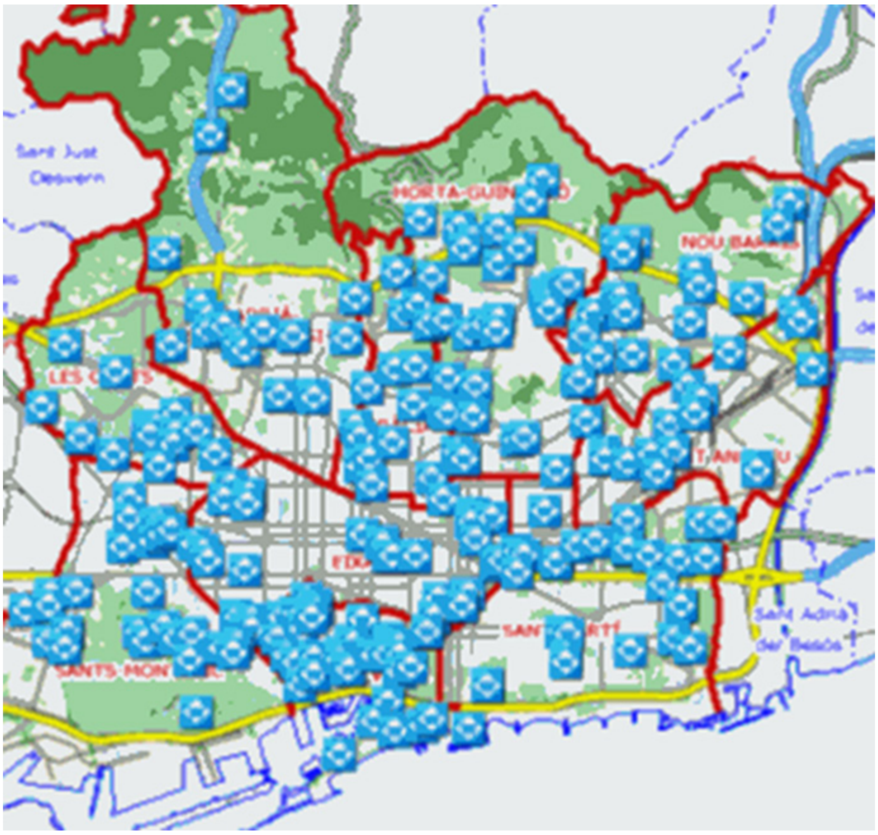
3.3 Other European WMAN deployments

3.3.1 Barcelona municipal Wi-Fi network, Spain

Barcelona has a city-wide Wi-Fi network which comprises two distinct mesh networks, one for municipal use only and another one for the public. The municipal network is based on a fibre core network with access points installed on traffic and street light poles. This network is intended to cover more than 30 per cent of the city using more than 400 meshed access points. Some of the municipal services served by the network were previously served using GPRS/UMTS connectivity, so the network aims to reduce operational costs, increase service reliability and security, and make new applications available or easier to deploy. Barcelona uses its network for (among other things) parking meter control, running wireless cameras to detect traffic light violations, providing bus information, and managing the public bicycle rental service.

The public Wi-Fi network is based in public facilities such as libraries, markets, and parks, and offers indoor and outdoor connectivity. This network of around 200 hotspots offers free Wi-Fi access subject to acceptance of the terms and conditions; no further registration is required. To meet the requirements set by the Spanish regulator to avoid distorting the market, the connection speed is limited to 256 kbps, and voice over IP is prohibited.

Figure 3-1: Barcelona municipal Wi-Fi network public access points



Source: MuniWIreless

3.3.2 Pan OULO network, Finland

The city of Oulu in Finland provides free wireless Internet access to all users at various locations across the city, including the market square area, city library, and the ice stadium. The network comprises over 1200 hot spots and claims to be Finland’s largest public Wi-Fi network in terms of user numbers and coverage.

3.3.3 ZapFi, Belgium

ZapFi provides free outdoor Wi-Fi access in the city centre of Bruges, using dual-band Alvarian infrastructure. The network is funded by targeted advertising on behalf of ZapFi’s partners. The network provides enhanced capacity at key locations, such as the local football stadium which is served by 8 access points and also provides Wi-Fi access to staff and students at a local College. The network is largely aimed at mobile users and supports SIM-based card authentication, making the transition seamless for users when registering on the ZapFi network

4 CURRENT STATUS OF WI-FI FREQUENCY BANDS

4.1 Introduction

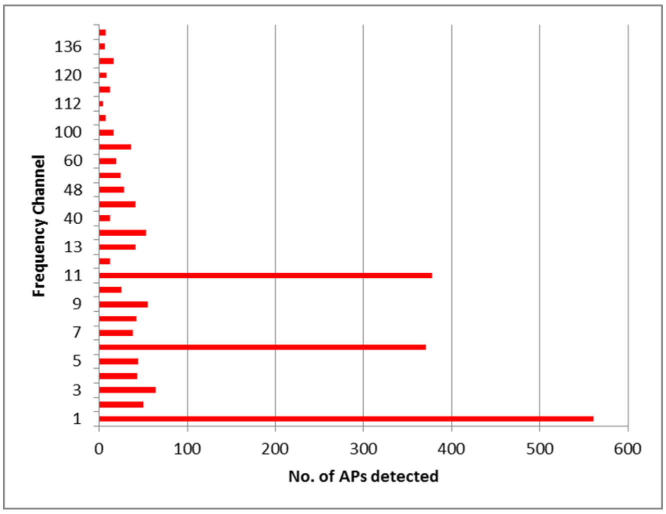
For our spectrum demand analysis in chapter 5 we will be focussing primarily on the 5 GHz Wi-Fi spectrum, which has far more capacity than the 2.4 GHz band and is widely considered to be essential to support future traffic growth. However, whereas the 2.4 GHz band has been widely deployed for many years in both the consumer and enterprise segments, use of 5 GHz has until recently been limited to a few high-end enterprise systems. This makes it difficult to draw on hard experience in terms of the level of interference or contention that might arise in this band in the future (and hence how intensively it might be possible to use the band). To overcome this, in our scenario analyses presented in chapter 5, we have undertaken some high level modelling to estimate the degree of contention that might arise at 5 GHz based on experiences at 2.4 GHz and our understanding of the differences between the band (notably in terms of radio propagation and frequency re-use).

It is helpful however to review briefly the current status of the two bands in terms of actual deployments, not least to gauge the extent to which the limited capacity in the 2.4 GHz band is meeting current demand. In the following sections we present a brief analysis of the extent of relative deployment of the two bands in private and public networks in the UK.

4.2 Current status of Wi-Fi deployment in the 2.4 GHz and 5 GHz bands

The following charts illustrate the number of access points detected on each 2.4 and 5 GHz Wi-Fi channel during a series of walk around surveys covering the Victoria, Westminster, South Bank, Covent Garden and City areas of London. Three sets of data are shown, covering (i) all APs, (ii) APs operated by O2 Wi-Fi and (iii) APs operated by BskyB-owned The Cloud. The latter two networks are the only WMANs known to be currently deploying dual band networks and appear to be the largest individual users of the band in the London area.

Figure 4-1 5 GHz channel deployment in London (all detected APs)



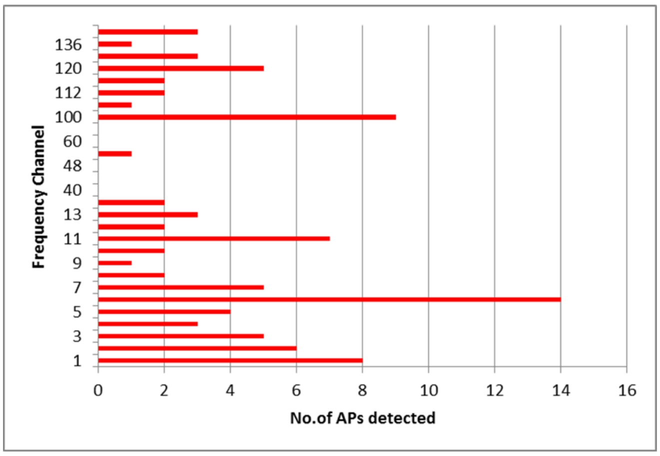
All detected APs

Channel distribution

2.4 GHz: 85.6%
Lower 5 GHz: 10.6%
Upper 5 GHz: 3.8%

Public networks appear to be main users of 5 GHz

Figure 4-2 5 GHz channel deployment in London (The Cloud)



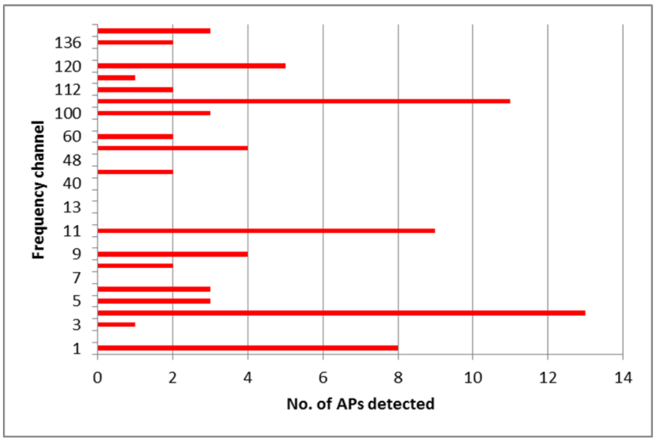
The Cloud APs

Channel distribution

2.4 GHz: 68.1%
Lower 5 GHz: 3.3%
Upper 5 GHz: 28.6%

Up to a third of users already connecting at 5 GHz

Figure 4-3 5 GHz channel deployment in London (The Cloud)



O2 WiFi APs

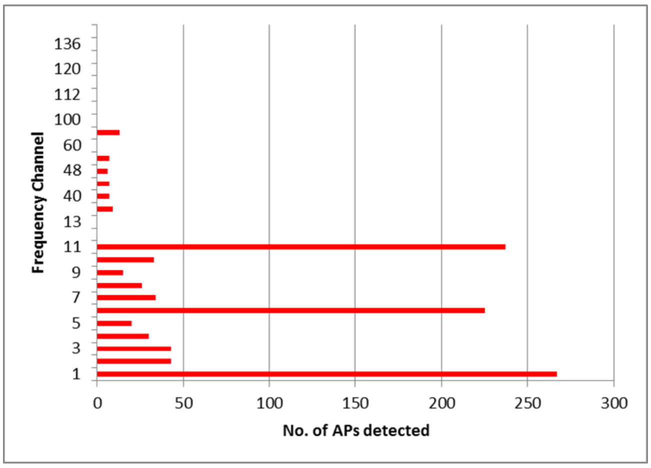
Channel distribution

2.4 GHz: 55.1%
Lower 5 GHz: 10.3%
Upper 5 GHz: 34.6%

Note the particularly high usage of the upper 5 GHz channels in the outdoor networks – this is a reflection of the constraint to indoor use that applies in the lower band. By comparison the majority of the private use of 5 GHz is in the lower band, which we believe is likely to be a reflection of the default setting of much of the dual band equipment currently available.

Whilst the level of 5 GHz use overall is small, it is nonetheless greater than is apparent in other parts of the world with a high Wi-Fi penetration. For example, a recent similar walk around survey carried out in the central district of San Francisco in the USA revealed that the upper band does not appear to be used at all and there is no use of 5 GHz currently by public Wi-Fi operators. This is probably a reflection of the stricter DFS[20] rules for protection of radar systems that applied until recently in the US, relative to Europe. Note also the absence of channels 12 and 13 in the 2.4 GHz band (these channels are not allowed in the US)

Figure 4-4 5 GHz channel deployment in San Francisco (all detected APs)



All detected APs

Channel distribution

2.4 GHz: 95.2%
Lower 5 GHz: 4.8%
Upper 5 GHz: 0%

Similar surveys conducted in suburban residential areas near London revealed no detectable 5 GHz access points.

The implication is that the existing 2.4 GHz band is still proving sufficient to meet current demand in most situations, despite having only three non-overlapping 20 MHz channels (compared to nineteen in the 5 GHz band). However, we expect to see substantial growth in the deployment of dual band systems over the next few years, in line with our analysis (chapter 5) which suggests that this will become essential to support projected traffic growth and support bandwidth hungry applications like high definition video.

4.3 Other uses of the Wi-Fi bands

The 2.4 GHz and 5 GHz bands are not exclusively reserved for Wi-Fi applications and the 2.4 GHz band in particular is heavily used by a wide range of other licence exempt applications. This band is also widely used by industrial, scientific and medical (ISM) equipment such as industrial heaters and domestic microwave ovens.

[20] Dynamic Frequency Selection

Parts of the 5 GHz band are shared with radar systems which are the primary users of the band and must be protected from interference arising from Wi-Fi systems.

In this section we briefly review the other uses of the two Wi-Fi frequency bands and the implications for Wi-Fi deployment in the future.

4.3.1 2.4 GHz

The following table provides a summary of non-Wi-Fi uses currently existing or expected to be introduced in the 2.4 GHz band, based on a recent survey of publicly available information by Aegis Systems.

Figure 4-5 Main non-Wi-Fi uses of the 2.4 GHz band

Technology	Extent of use	Comments
Bluetooth	Widely used for a range of applications including wireless keyboards, mice, toys and game controllers, audio feeders, home and industrial automation and medical applications.	Low power and frequency hopping helps to mitigate interference but some interference may arise, e.g. in domestic environments where used for computer peripherals or audio applications
ZigBee	Widely used in industrial and consumer control and automation applications (e.g. heating controllers). Some outdoor use, e.g. for traffic light controls	Low power and low duty cycles help to mitigate interference but occasional interference may arise
Analogue	Historically has been widely used for video applications including domestic video senders, CCTV and baby monitors.	Generally operate close to the band centre (2.45 MHz) and can generate significant interference in this part of the band where co-located with Wi-Fi systems
ISM	Microwave ovens	Widely deployed in homes and businesses, RF leakage may cause interference where co-located with Wi-Fi systems. Interference generally limited to around the centre of the band

There is also some limited deployment of RFID devices in the band, although usage is expected to remain relatively low as other more suitable bands exist.

The impact of these other systems where deployed in close proximity to Wi-Fi will be generally to slow down the transmission speed or to cause the access point to switch to an alternative channel where such a capability is available. Bluetooth devices use frequency hopping technology which co-exists relatively well with Wi-Fi because co-channel interference only arises intermittently – indeed Bluetooth and Wi-Fi can be deployed simultaneously on the same device (e.g. to provide a wireless audio output from a wireless internet device) without any noticeable degradation to either application.

Probably the most significant sources of interference to Wi-Fi in this band is from analogue devices such as video senders and baby alarms, although these are generally constrained by the short range devices (SRD) regulations to operate in the centre part of the band and therefore less likely to affect the highest and lowest frequency channels. Similarly, RF leakage from microwave ovens has most impact on the centre part of the band. These applications are also generally used indoors and hence less likely to have a significant impact on outdoor WMAN deployments. Video senders are in future more likely to deploy Wi-Fi technology in the 5 GHz band, which can support high definition (HD) transmissions and support multiple streams.

4.3.2 5 GHz

Unlike 2.4 GHz, the 5 GHz Wi-Fi bands are relatively clear of other uses, since licence exempt operation is limited to Wi-Fi, with other SRD applications using the adjacent 5.8 GHz band. However, the band is shared with military and civil radar applications, which take precedence over Wi-Fi systems in the band. As a result, constraints apply to Wi-Fi deployment at 5 GHz to protect these radar systems.

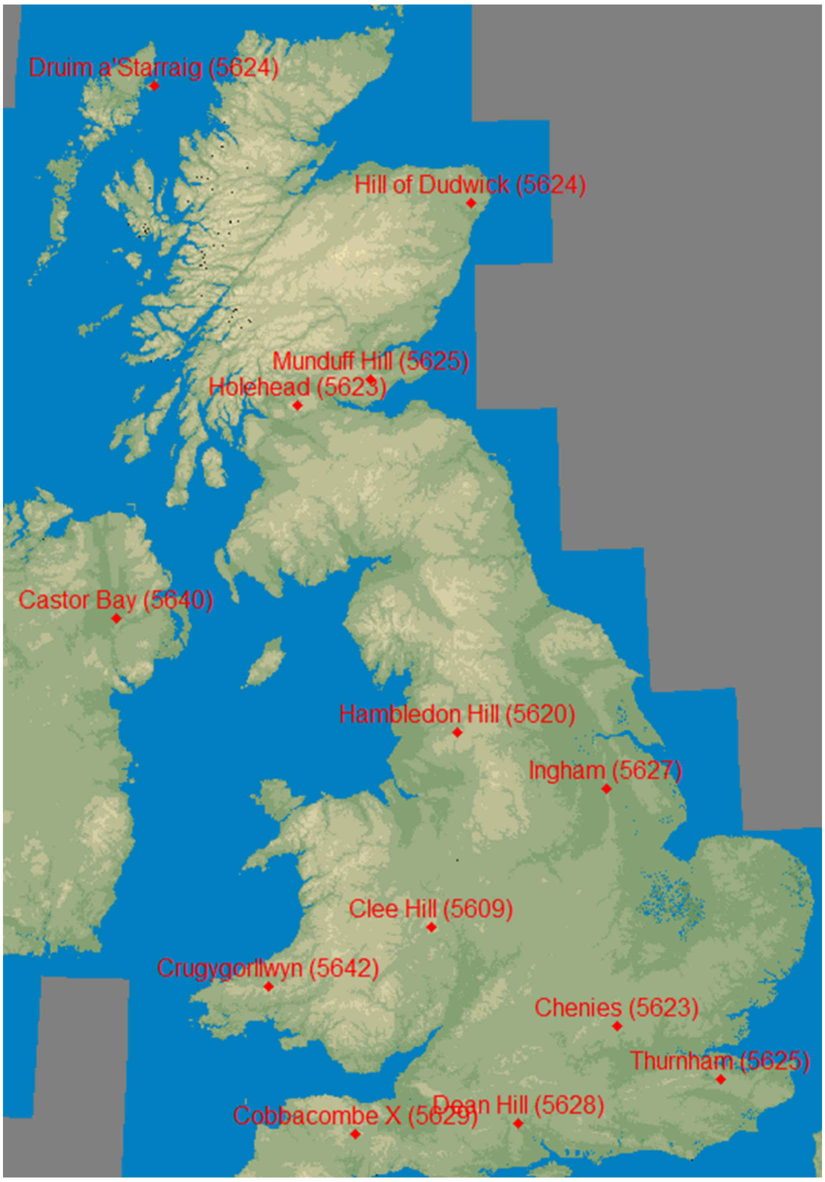
All Wi-Fi systems operating in the bands 5250-5350 MHz or 5470-5725 MHz are required to comply with the dynamic frequency selection (DFS) requirements contained in the ETSI standard EN 301 893. This effectively requires Wi-Fi systems to detect and avoid radars with particular characteristics. The DFS requirements have been amended from time to time to incorporate additional radar characteristics that were not covered by earlier versions. Wi-Fi systems operating in the 5150–5250 MHz band do not require DFS but are restricted to indoor use. The 5250–5350 MHz band is also restricted to indoor use as well as requiring DFS.

The main impact of these restrictions has been that some 5 GHz Wi-Fi equipment that does not support the latest DFS requirements have had access to the channels above 5250 MHz disabled, and this has probably been a significant factor in delaying the take-up of the band so far. However, most professional Wi-Fi equipment does now support the latest requirements and can operate over the entire band.

In practice the DFS requirements do not appear to have had an adverse impact on the deployment of 5 GHz access points in WMAN applications in the UK so far. As we have seen in section 4.2 the two largest outdoor WMAN networks (O2 Wi-Fi and The Cloud) both make use of these upper 5 GHz channels in their networks in central London.

One of the main radar applications in the UK is for weather radars, operated by the Met Office. There are 14 of these radars, all operating in the 5620 – 5640 MHz range. The locations of these radars and their operational centre frequencies (in MHz) are shown below. Note that we believe there are also a number of military radars operating in the band but details of these are not available.

Figure 4-6 Location of Met Office 5 GHz weather radars in the UK[21]



Our survey in central London suggested that use of channel 124 (5620 MHz), which overlaps with frequencies of the two radars nearest to London is used to a similar extent to other frequencies in the band, implying that these radars do nor compromise 5 GHz use in this area. This assessment was confirmed in our discussions with both O2 Wi-Fi and The Cloud.

[21] Source: EUMETNET Opera data base

5 ANALYSIS OF POTENTIAL WI-FI SPECTRUM DEMAND AND BENEFITS OF TECHNOLOGY ENHANCEMENTS IN VARIOUS WI-FI DEPLOYMENT SCENARIOS

5.1 Introduction

In this chapter we consider the potential demand for Wi-Fi capacity and radio spectrum over the next decade in three typical operational scenarios, each of which has been chosen to represent a relatively high demand location. Our approach involves consideration of three principal factors, namely:

- Projected traffic levels for various user categories (e.g. business, residential, public hotspot, outdoor WMAN , noting that in general there will be a mix of user types and this mix will vary by scenario
- Estimated throughput capacity per access point (this will vary by scenario and user type)
- Estimated spectrum re-use capability (i.e., how much physical separation is required between co-channel access points to avoid contention or co-channel interference arising.

For each scenario we consider how technological developments might facilitate improvements, e.g. with regard to access point throughput, frequency re-use or traffic balancing across access points.

It should be noted that such analysis inevitably involves a high degree of uncertainty, particularly with regard to future traffic projections and the nature of indoor radio propagation[22]. Building layout, materials (walls and ceilings), fixtures and fittings can make a significant difference to the distance that radio signals propagate and hence the quality of coverage and re-use capability.

The three deployment scenarios that have been considered are:

iv) Dense urban location with a mix of business, residential, indoor hotspot and outdoor MAN deployments

v) High density residential building

vi) Business Park with high density enterprise network

In each case we have considered the likely demand for spectrum to support the existing and projected future residential and/or business use and the impact that deploying one or more outdoor WMANs at the same location might have on

[22] See for example Aegis et al "In-home propagation", final report for Ofcom, June 2011 for a more in-depth consideration of indoor propagation

spectrum demand. We have also considered the implications of the WMANs operating either as single band (2.4 GHz or 5 GHz) or dual band systems.

For the first scenario we have chosen a real location with a particularly high level of Wi-Fi deployment and our analysis reflects the actual number of access points detected at the busiest location. For the other two scenarios, which are more hypothetical in nature, we have used a modelling approach to estimate the degree of contention and spectrum re-use that might arise.

Our description and analysis of each of the three scenarios is presented in the following sections.

5.2 Scenario 1: Dense Urban location with mixed traffic (residential, business and both indoor and outdoor public)

5.2.1 Scenario Description

We have chosen a real location to represent this scenario, namely the Covent Garden area in central London. This location is particularly interesting in the context of WMAN deployment as it already supports two separate outdoor WMAN networks, each with extensive and partially overlapping coverage. These operate alongside a very high density of indoor access points, supporting both private (business and residential) and public (indoor hotspot) locations. We therefore consider this area to represent something close to a worst case scenario in terms of access point density and traffic mix.

5.2.2 Access Point Density

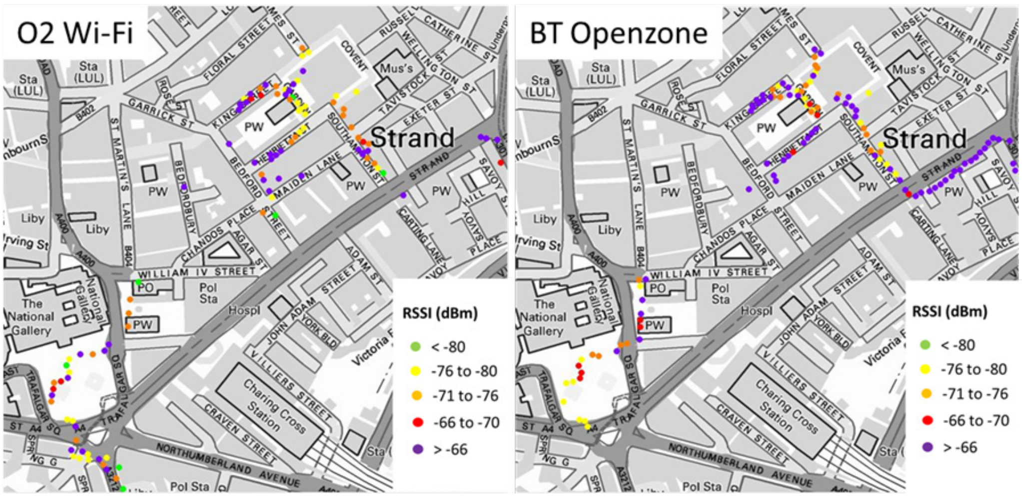
The figure below shows the number of 2.4 GHz signals detected outdoors (at street level) at various locations in the Covent Garden area, at a signal level of -85 dBm or greater. This is a sufficient level to result in contention with other systems operating on the same or overlapping frequency at the same location. It can be seen that many locations have 30 or more APs visible; in the worst case locations over 60 APs can be detected. Hence the contention ratio per non-overlapping 2.4 GHz frequency channel in this area is typically in the range 10 – 20. This is comparable to the contention ratio that typically applied in early DSL broadband deployments. After traffic overheads and location variability of client devices are taken into account, this is likely to provide a typical average data capacity per AP in the range 1 – 2 Mbps. This is sufficient to support less demanding applications such as web browsing but would be unlikely to cope reliably with more intensive applications such as HD video streaming or delay intolerant applications like voice over IP.

Figure 5-1 Number of access points detectable outdoors at various locations around Covent Garden, London

5.2.3 WMAN availability in the area

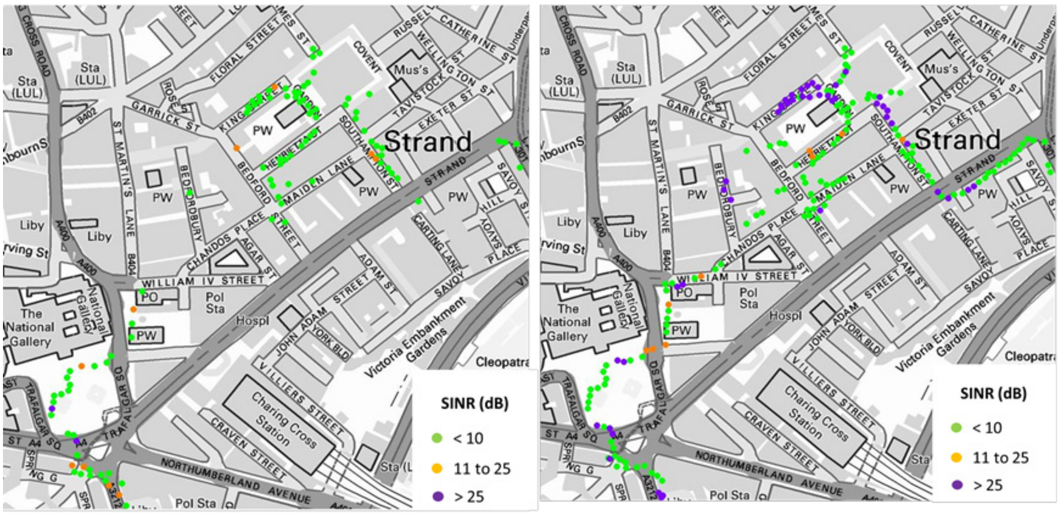
Both BT Wi-Fi and O2 Wi-Fi deploy outdoor access points in this area, which provide extensive coverage with significant overlaps, as illustrated below (note that these maps show access points at selected locations only and a comprehensive indication of the coverage provided by the networks).

Figure 5-2 BT Wi-Fi and O2 Wi-Fi outdoor AP availability at selected locations in Covent Garden



Whilst the signal level in both networks at most locations is adequate to provide a reasonable throughput in the absence of other competing traffic, the situation is less favourable when interference and contention is considered. The figure below shows the ratio of the BT and O2 signals detected to the highest other co-channel Wi-Fi signal at the same location. As can be seen there are very few locations where the 25 dB or more that is required to ensure an uncontended connection is achieved and in much of the coverage area the ratio is less than 10 dB.

Figure 5-3 O2 Wi-Fi and BT Wi-Fi outdoor AP SINR values

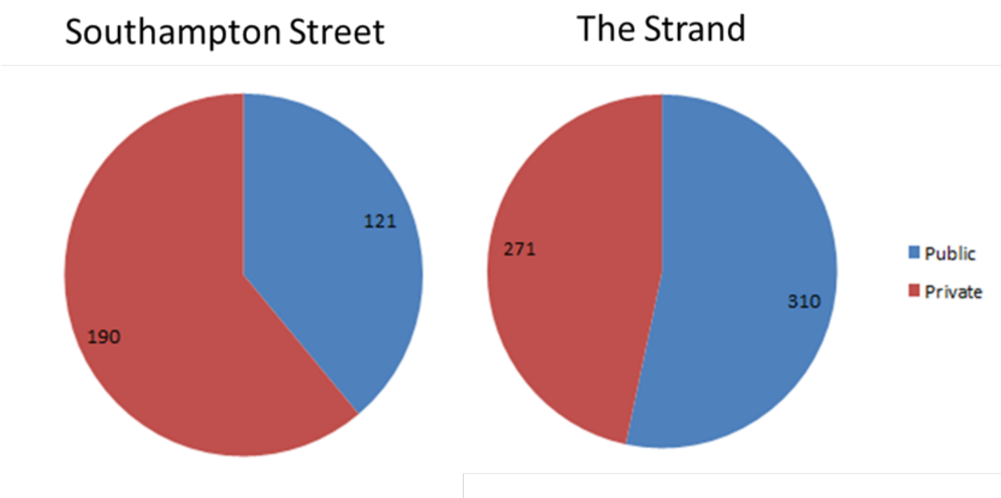


With current levels of traffic this contention is unlikely to have a significant impact, except perhaps at the busiest times, although at locations where the SINR is very low (<10 dB) there may be difficulties connecting at times. However as traffic grows both on the WMAN networks and the nearby private WLAN networks it is increasingly likely that the 2.4 GHz spectrum will become saturated. O2 is already deploying 5 GHz in its network, but BT appears not to be (though we have been unable to verify this with directly with BT). Consistent with our findings in section 4.2, very few of the private networks detected appear to be deploying 5 GHz.

5.2.4 Balance of public and private APs

The Covent Garden area has an unusually high proportion of public Wi-Fi access points, reflecting the large number of tourists and business travellers who visit the area. In addition to the two outdoor networks referred to above there are also a large number of indoor public hotspots, a significant proportion of which are operated by the two WMAN operators, BT Wi-Fi and O2 Wi-Fi. The area is also home to a broad mix of offices, shops, hotels, restaurants and residential accommodation.   The split between public and private signals at two of the most congested locations (the southern end of Southampton Street and The Strand between Lancaster Place and Savoy Court) is illustrated below. In the latter case over half of the access points detected are indoor or outdoor public hotspots.

Figure 5-4 Proportion of Public and Private Wi-Fi signals (visible outdoors)



5.2.5 Implications of 5 GHz deployment

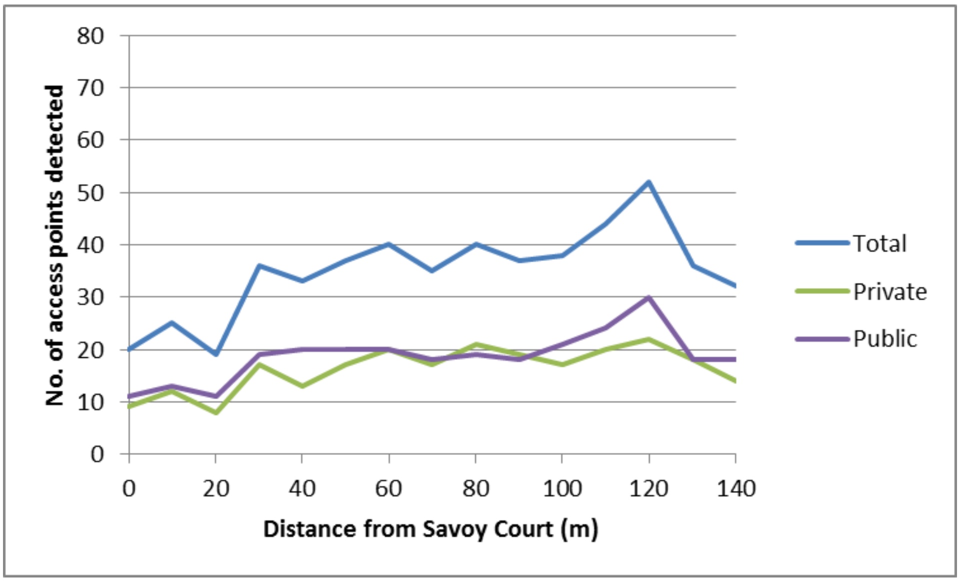
The above analysis refers to 2.4 GHz deployments, which account for a large majority (86%) of all of the currently installed access points in the area. The situation at 5 GHz would be much more favourable from a channel contention perspective since (a) there are many more channels available and (b) the radio signals incur more attenuation at 5 GHz, although the latter may in some instances be partially offset by the higher powers that are permitted.

To estimate the number of 5 GHz APs that would be visible outdoors assuming the same AP density as at 2.4 GHz today, we have assumed that the signal at street level would be on average10 dB lower than the signal that would be detected from a 2.4 GHz AP[23]. Assuming the same detection / contention threshold of 85 dBm applies in both bands, this means that only those 2.4 GHz APs with a detected signal of -75 dBm would be likely to exceed the threshold at 5 GHz (because of the additional 10 dB attenuation).

At the busiest location, along The Strand, the number of visible 2.4 GHz access points with detected RSSI values above -75 dBm is as follows:

[23] This is based on results from a number of measurement campaigns undertaken by Aegis

Figure 5-5 Number of detected Wi-Fi signals above -75 dBm along The Strand

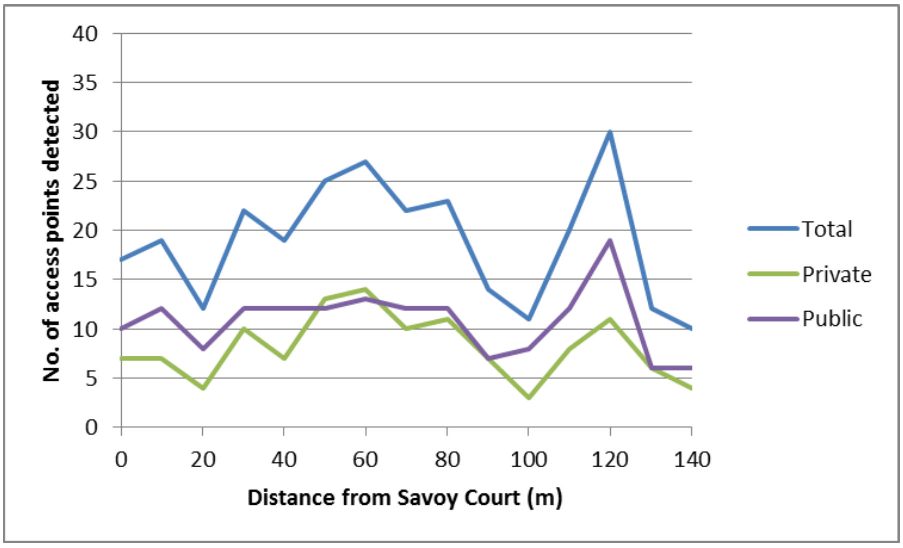


These numbers provide an indication of the number of neighbouring access points that would be visible outdoors at each location, which can be used to estimate the likely contention ratio on each frequency channel, by dividing the number of visible access points by the number of available channels. At the worst case location it can be seen that a total of 52 APs are visible, of which 30 are public (indoor or outdoor) and 22 are private. This implies an overall contention ratio of 2.74:1 if 20 MHz channels are used and the whole 5 GHz band is available, or 5.78:1 if 40 MHz channels are used[24]. Note however that not all of the available channels can be used outdoors so contention will be greater if there is a significant proportion of outdoor access points.

The situation indoors is more favourable since many of the neighbouring APs that are visible outdoors will be subject to a further attenuation of 10 dB or more in neighbouring buildings due to building penetration losses – the resulting improvement is indicated in the following figure which shows the number of visible access points with an outdoor signal level at 2.4 GHz of -65 dB or greater – corresponding to an indoor signal at 5 GHz of -85 dBm, the threshold at which contention is likely to occur.

[24] Based on nineteen 20 MHz channels or nine 40 MHz channels, in accordance with the European channel plan

Figure 5-6 Number of detected Wi-Fi signals above -65 dBm along The Strand



In this case the number of visible APs is reduced to a total of 30 (18 public and 11 private) and the contention ratio is reduced to 1.58:1 for 20 MHz channels and 3.3:1 for 40 MHz channels. The degree of contention that is likely to be tolerable in practice will depend on the level of traffic, which is projected to rise significantly over the coming years. In the following section we present our view of the level of wireless traffic demand that might exist for residential, business and public Wi-Fi access points.

5.2.6 Estimating traffic demand

In the following sections we consider the potential traffic demand from the three principal Wi-Fi categories (residential, business and public).

5.2.6.1 Residential traffic projections

Currently, the dominant source of Wi-Fi traffic in most homes is fixed Internet data; however, estimates vary as to the actual level of Internet traffic carried over the fixed networks. Probably the most oft-quoted source of such estimates is the Cisco Visual Networking Index (VNI). The table below shows the estimated average and busy hour internet traffic for Western Europe, according to Cisco, for 2011 and 2016.

Table 2 Internet data traffic estimates for 2011 and 2016

Parameter	2011	2016	CAGR
Average total Internet traffic (Terabits per second)	3	11	30%
Busy Hour total Internet traffic (Terabits per second)	7	26	30%
Number of Internet Households (million)	20	22	1.9%
Average Busy hour traffic per household (Mbps)	0.35	1.18	28%

Extrapolating these growth rates to 2024 yields an estimated average busy hour bit rate of 8.5 Mbps per household.

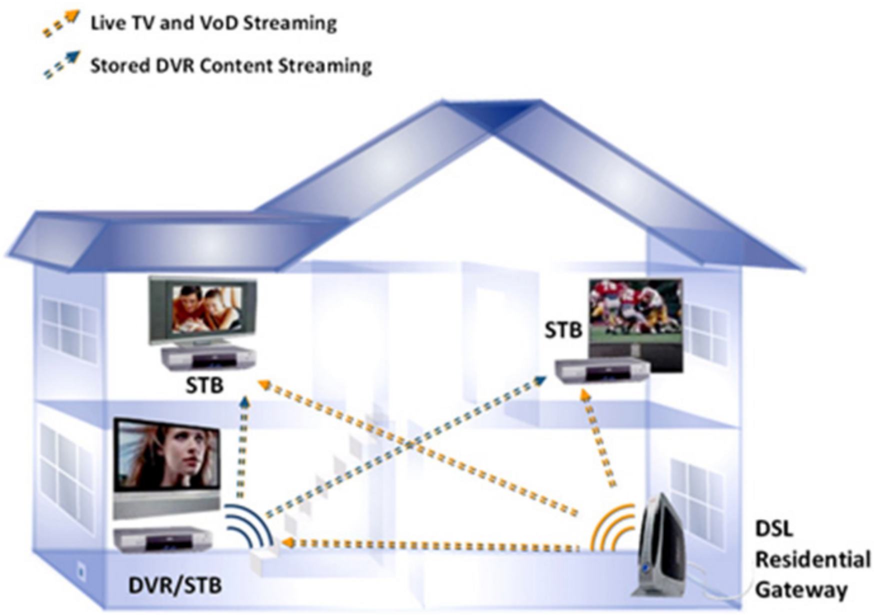
Internet usage varies significantly between households, with the heaviest users consuming many times more data than low or average users. For example, according to Ofcom, 10% of high speed broadband users account for 50% of the total high speed broadband traffic. The busy hour traffic for these higher usage households is therefore five times the average, which would imply an average busy hour bit rate for these highest users of more than **42 Mbps** per household by 2024. Since our analysis is attempting to estimate potential future demand at the busiest locations (which is ultimately what will drive Wi-Fi spectrum demand), we have assumed that a city centre location like Covent Garden will have a high proportion of such large users and have therefore used this figure in our traffic demand forecast.

Off-network wireless data traffic is also likely to be a significant factor in residential locations in the longer term. A number of companies are already marketing "wireless home theatre" solutions which use Wi-Fi technology to distribute high definition audio-visual content around the home. For example, Israeli company Celeno, whose backers include Cisco and Liberty Global, is marketing a product which it claims it capable of distributing up to eight simultaneous high definition video streams around the home. Celeno's products are already being deployed in Europe, for example by Bouygues Telecom in France and Deutsche Telecom in Germany. In Belgium, Belgacom is using Ruckus Mediaflex wireless IPTV distribution equipment, which also uses Wi-Fi, as an alternative to indoor cabling to provide a more flexible and cost-effective approach to cable TV installation. So far the technology has been taken up in 25,000 households.

Wireless in-home video distribution is a relatively niche market currently, however the track record of previous technological innovations in the audio-visual sector suggests it could well become a mainstream product by 2024. For example, DVD players achieved an installed base of over 100 million in Europe within seven years of launch. Since a single HD video stream requires approximately 8 Mbps of bandwidth, and since it is realistic to assume a typical household may be viewing two or three independent streams at peak viewing times, this suggests such systems could over time require access to uncontended bandwidth of **24 Mbps** or more.

Although some of this traffic may originate from the external broadband connection (and hence be included in the 42 MHz bandwidth determined above), in many cases distribution is likely to be via a separate personal video recorder (PVR) hub, as illustrated below, which would require separate streams to link to the home gateway and the viewing device. The off-net traffic in such circumstances is additional to the internet video traffic, even if the content is essentially the same.

Figure 5-7 Example of in-home video distribution system[25]



Hence for high usage residential users we estimate the potential traffic demand per household in 2024 could be as follows:

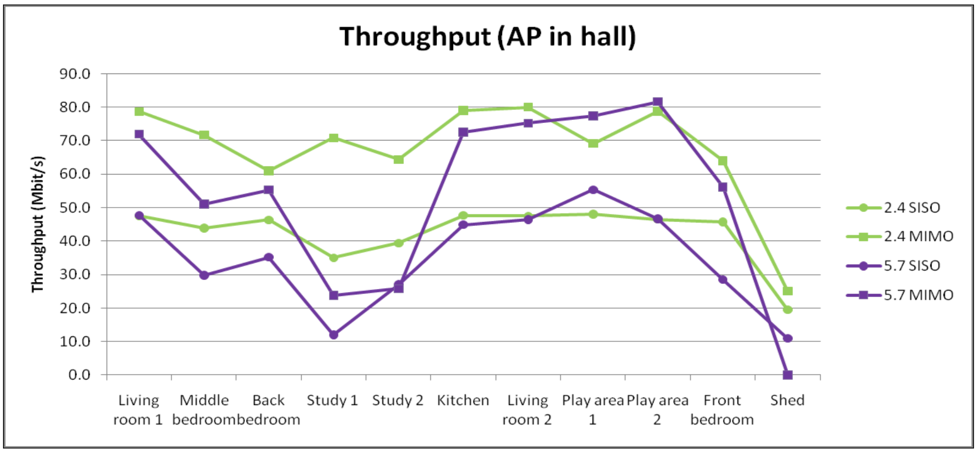
- Fixed internet Traffic: 42 Mbps
- Off-net traffic: 24 Mbps
- **Total estimated traffic per household: 66 Mbps**

Actual usable throughput for a residential access point will be lower than the headline values quoted by vendors, due to protocol overheads and location variability of client devices (which means not all will be close enough to operate at the highest bit rates). For example, the figure below shows the actual bit rates (based on file downloads) achieved in a typical suburban house from an 802.11n access point using single stream (SISO) and 2x2 MIMO configurations, from a recent Ofcom study[26].

[25] Source: Celeno

[26] Indoor propagation study final report for Ofcom by Aegis Systems et al, June 2011

Figure 5-8 Measured throughput from an 802.11n access point in a typical suburban dwelling (20 MHz channel)



Taking account of the typical real average throughput likely to be achieved from a residential access point after allowing for protocol overheads and the distribution of connected devices around the home, our estimated traffic level of 66 Mbps would imply a requirement for 40 MHz of uncontended spectrum per household.

We note that in some cases access to additional RF bandwidth may be required, e.g. to support the higher bit rates offered by the new 802.11ac standard or where multiple access points are required to provide adequate coverage throughout a dwelling.

In the former case, the higher throughput available from a wider channel bandwidth would allow greater sharing of frequency channels between neighbouring access points assuming the traffic level is the same, so overall spectrum demand should in principle be unchanged, though there may be an impact on 802.11ac performance at busy times if there is a high density of legacy 802.11n networks nearby, The current fragmentation of the 5 GHz band also limits the proportion of the 5 GHz band that can be used by wider channels.

The latter scenario would tend to arise in larger dwellings or those where internal attenuation is higher, in which case we would expect the additional spectrum demand within the household to be largely offset by reduced visibility of neighbours' access points, since these would be more widely separated and/or subject to additional attenuation. Overall spectrum demand would therefore be substantially unchanged.

5.2.6.2 *Business Traffic*

There is little available data to enable us to derive meaningful estimates of business data traffic in a mixed environment such as this. However, observation of the types of businesses at a location such as Covent Garden suggests that business use in such areas is likely to be dominated by SMEs (retail, food and drink, professional services etc) rather than large corporate premises. For such users, we assume that wireless traffic would be predominantly internet based and that broadband connection speeds are likely to be similar to those for residential users, i.e. of the order of 100 Mbps in the longer term[27].

However, business traffic is less likely to be dominated by high bandwidth real-time applications like HD video and projected growth rates are somewhat lower than for residential use (c. 25% according to Cisco's Visual Networking Index projections for 2011-2016, compared to almost twice this for consumer data). A greater degree of contention is therefore likely to be possible, particularly in small to medium enterprises (SMEs) which are likely to account for the bulk of business use in this mixed traffic scenario such as we are considering here.. Furthermore, peak business traffic tends to occur during the morning and afternoon, whereas the residential peak tends to be in the evening, hence some contention between business APs and nearby co-channel residential APs is likely to be feasible during the working day in a mixed residential / business environment.

We are therefore of the opinion that a single **40 MHz** channel would generally be sufficient to meet the needs of individual business users in this scenario and that contention between two users or more per channel should also be acceptable. From time to time access to higher bandwidth (in excess of 100 Mbps) may be required, e.g. to support large file downloads or data backups. The wider channels provided by 802.11ac would be beneficial in this regard, As in the residential case deployment of these channels would provide greater scope for frequency channel sharing, leaving the overall spectrum demand relatively unchanged.

5.2.6.3 Public Wi-Fi Traffic

Traffic carried by public Wi-Fi hotspots has historically been a very small proportion of total wireless data traffic, however there are a number of factors that are likely to drive growth in this sector. In particular, greater ease of access to public Wi-Fi services through the improved interworking and roaming arrangements that we discussed in section 2.3 and the proliferation of Wi-Fi only wireless devices such as tablet PCs already appear to be pushing up traffic. For example, O2 Wi-Fi have told us that they have seen traffic levels up to 6 times higher on some of their outdoor Wi-Fi networks in London than on their cellular network in the same area and BskyB owned network The Cloud is finding increasing numbers of users streaming video over some of their (mainly indoor) hotspots. Both of these operators are now offering automated log-in facilities and are deploying dual band APs throughout their networks to provide greater speed and capacity. This greater convenience and ease of access is expected to drive traffic higher and both operators have told us that they anticipate long term congestion in the Wi-Fi spectrum as traffic grows.

Future traffic on public Wi-Fi networks is difficult to project given their relative immaturity. BT has stated that traffic over its public Wi-Fi network has grown by 100% over the last six months and 1000% over the last four years, but no data is

[27] This reflects the EU Digital Agenda Europe objective that 50% of broadband connections should have a headline speed of at least 100 Mbps by 2020.

available on absolute traffic levels. Such growth rates suggest that traffic levels could become significantly higher on such networks over time than on macro cellular networks where both options are available. This is further supported by O2 Wi-Fi's estimate of a traffic volume 5-6 times that of their local mobile network traffic in the busiest locations. In the absence of other quantitative data on public Wi-Fi traffic in the UK, we have made an estimate based on comparison between the capacity of a single mobile base station and a network of Wi-Fi hotspots serving a similar area, assuming such levels of traffic were to be maintained.

Assuming that the Covent Garden area is served by a single tri-sectored 3G base station per operator, comprising a total of fourteen 5 MHz carriers[28] per sector and that when fully loaded the base stations can carry a throughput of 3 Mbps per sector per carrier, the mobile network capacity for the area would be 3 x 3 x 14 = 126 Mbps. If six times that amount was assumed to be carried over the local public Wi-Fi hotspots, and that there 400 hotspots serving the area (fewer than we observed during our survey), this implies a peak traffic level currently of approximately 300 kbps per access point. Cisco's VNI is forecasting a 50% compound annual growth rate in mobile data traffic over the next few years. If this growth rate were to be maintained until 2024 this would imply that traffic would grow to as much as 17 Mbps per hotspot.

5.2.7 Spectrum Requirement to support projected Wi-Fi traffic

To translate the above traffic estimates to potential spectrum demand, it is necessary to consider the contention ratios and the degree of spectrum re-use that can be tolerated by the different user types.

5.2.7.1 Spectrum to support residential traffic

In the residential case, we have already determined that in the longer term (2024) access to up to 40 MHz of uncontended spectrum per household may be required. To estimate the total spectrum requirement, this bandwidth must therefore be multiplied by the number of residential access points that are likely to be visible at a given location, In section 0 we estimated that indoors up to eleven 5 GHz access points would be visible. If half of these are assumed to be residential and the other half business, this would imply up to 6 access points would be visible and that the total spectrum requirement to support residential Wi-Fi traffic in this scenario would be up to (6 x 40) = **240 MHz.**

5.2.7.2 Spectrum to support business traffic

For business users we have assumed that a contention ratio of 2:1 would be acceptable and that a 40 MHz channel would generally be sufficient for each user. Assuming up to six business access points are visible at an indoor location, this implies a spectrum requirement of (6 x 40 / 2) = **120 MHz** to support this traffic.

---

[28] This assumes that currently all of the 2 GHz spectrum is used plus two 900 MHz carriers.

5.2.7.3 *Spectrum to support public hotspot traffic*

Our survey found that the number of 5 GHz hotspots likely to be visible at indoor and outdoor locations was 18 and 30 respectively. Approximately one in four of the hotspots detected was believed to be an outdoor hotspot (based on the broadcast SSID), i.e. up to 8 outdoor hotspots were detected at the busiest location, however it should be noted that all of these were operated by the same network (BT). Our estimated long term (2024) traffic demand is 17 Mbps per access point. Assuming an uncontended capacity (after allowing for overheads) of 40 Mbps per 20 MHz channel implies a contention ratio of 2:1 for such channels would be acceptable. This would imply a spectrum requirement of 8 x 20 / 2 = 80 MHz[29] to support outdoor hotspot traffic in the area, A further 80 MHz would be required if Wi-Fi is used to provide meshing between WMAN access points, i.e. a total of 160 MHz could be required to support outdoor WMAN traffic.

The number of visible indoor hotspots is very high (about 14 typically detectable in an indoor location). However, we would expect the capacity of an indoor hotspot to be somewhat better than for an outdoor hotspot since (a) MIMO tends to be more effective indoors and (b) indoor hotspot users are more likely to be close to the access point and therefore benefit from a higher signal quality. We therefore think a typical throughput of 50 Mbps can be assumed which assuming a traffic demand of 17 Mbps per access point implies a contention ratio of 3:1 would be acceptable. This would imply a spectrum requirement of 14 x 20 / 3 = **100 MHz** to support indoor hotspot traffic in the area.

Note that because of the substantial overlap between indoor and outdoor public Wi-Fi systems there may be limited scope for frequency contention (sharing) between the two.

5.2.8 Summary of overall spectrum requirement

The table below summarises our estimates of long term spectrum demand for this scenario.

- Residential use: 240 MHz
- Business use: 120 MHz
- Public outdoor networks (access and meshing): 160 MHz
- Public indoor networks: 100 MHz
- **Estimated total spectrum requirement: 620 MHz**

[29] This has been rounded up to the nearest 20 MHz to reflect the Wi-Fi channelisation

5.2.9 Implications of co-ordination and interworking technologies

5.2.9.1 Impact of multiple WMAN operators

Co-ordination methods based on 802.11 extensions are not expected to play a significant role here, for the reasons explained in Chapter2. One exception may be beam forming, however it is known that directional antennas do not offer an advantage in all scenarios, especially when wanted and unwanted signal lie in the same direction. As deployments are un-coordinated between operators, there is no control over when this may happen. in any case the likely advantage is less than a doubling of efficiency, and this must be contrasted against likely traffic increases which are exponential.

5.2.9.2 Impact of network discovery protocol technologies

As we discussed in Chapter 2, both Hotspot 2.0 and ANDSF are intended to transform the usage of hotspots by the public into a no-effort, seamless process. This is expected to boost public Wi-Fi usage well above its present low level of around 4%[30].

As well as this advantage for the user, the advantage for the operator is that users may be efficiently attached to the most suitable network and that management traffic (including for example the broadcasting of many SSIDs) will be reduced.

A further advantage for user and operator alike is that there are cases where seamless IP session mobility may be offered to an application. For the user this means that applications do not suffer delay or disconnection when roaming around any cellular and Wi-Fi networks. For the operator this means that they still retain control of the user when roaming away from the cellular network occurs. For this to happen, the user traffic must transit the cellular network core regardless of whether Wi-Fi or cellar access is being used. Hotspot 2.0 and ANDSF can accommodate this without modifications such as secure tunnels being needed on the handset. In effect, Wi-Fi access becomes a trusted access method to the cellular core when Hotspot 2.0 is used, which is major change to how Wi-Fi has been viewed by cellular operators. However where a user roams to a Wi-Fi network with a direct Internet connection, then IP mobility is not guaranteed.

Our conclusion is that network discovery protocols like Hotspot 2.0 will hugely increase public Wi-Fi adoption and they will do so in manner which avoids unnecessary inefficiencies in the network. Overall therefore, they are an enabler for increased usage and are likely to increase the demand for spectrum.

5.2.10 Implications of single band vs. dual band operation

The above analysis has been carried out on the assumption that in the long term the majority of Wi-Fi access points (indeed all of those carrying the highest traffic levels) would be dual band and that the majority of traffic would be conveyed in the 5 GHz

[30] Source: Ofcom’s infrastructure report.

band. This is of course a very different situation from the present one, where almost 100% of private traffic and most of the public traffic is carried at 2.4 GHz.

At current levels of traffic, the 3 – 4 non overlapping frequency channels available have so far proved sufficient to meet demand in most cases. However, as we discussed in section 5.2.6, residential traffic in particular is expected to rise rapidly over the next decade, driven mainly by increasing online and offline wireless video. This could lead to levels as high as 50 Mbps per household at peak times in some locations.

The capacity of the current 2.4 GHz band is far more limited than the 5 GHz band, for three principal reasons, namely:

i) Fewer frequencies available

ii) More restricted re-use at 2.4 GHz (due to longer propagation distances)

iii) More likelihood of interference from other non-Wi-Fi applications.

In section 5.2.2 we estimated the currently level of contention per channel in the 2.4 GHz band in this scenario to be in the range 10–20, equating to a typical capacity per household, business user or public hotspot of less than 2 Mbps. Whilst this would have been adequate when DSL speeds were generally of a similar order, it is clearly not compatible with the UK and European objectives of delivering ubiquitous super-fast broadband (30 Mbps or more) by 2020. We do not therefore consider 2.4 GHz to be sustainable as the primary means of delivering wireless connectivity in the longer term.

The band will, however, continue to play an important role, both in supporting legacy client devices that do not have 5 GHz capability and in providing coverage fill-in or extension in areas that are beyond the reach of 5 GHz signals. This could be of particular benefit in extending the range of WMAN networks or public hotspots, particularly where the latter are configured primarily to support private use, such as the BT FON network.

5.3 Scenario 2: High Density Residential environment

5.3.1 Scenario Description

For this scenario we have taken a more hypothetical approach based on a high density multi-occupancy building such as a city centre apartment block. In such a scenario it is helpful to consider how the signal from a typically located access point will propagate within the user's own apartment and neighbouring homes. The scenario assumes three parallel apartment blocks each comprising 16 back to back single story apartments each of dimensions 5m x 5m and separated by a walkway of 10m width.

5.3.2 Traffic projections

Similar traffic projections are assumed to those generated in section 5.2.6.1, i.e. a requirement for up to 66 MHz uncontended RF bandwidth per household in the longer term (2024).

5.3.3 Spectrum re-use Analysis

The spectrum required to support the projected level of traffic per household in a high density residential location can be estimated my modelling the radio signal propagation from a typical domestic access point and using this to estimate the separation required between co-channel access points to avoid contention between them. The modelling used has been carried out using an Excel based model and using the Extended Hata indoor SRD propagation model[31].

In practice, the extent to which radio signals propagate depends on many factors, but two of the most significant are the frequency band (which determines the basic free space path loss) and losses incurred by transmission though walls and ceilings (referred to hereon as “wall loss”. In the following figures, the signal level from a centrally positioned access point is categorised into four ranges, namely:

- Above -60 dBm (red): this will generally ensure reliable, contention free connectivity so long as other co-channel signals or interference does not exceed -85 dBm (i.e. a CINR of 25 dB or greater)
- -60 to -85 dBm (orange) : this will generally provide connectivity but is likely to be contended in the presence of other co-channel signals. To avoid contention, we consider that any location where the signal from a neighbouring AP falls into this category should not use the same frequency.
- -85 to -95 dBm (pink): at this level contention is unlikely to arise to another co-channel indoor AP as long as the wanted signal is 60 dBm or greater, however this level may cause contention with co-channel outdoor connections where the signal level may be lower than in the indoor case.
- Below -95 dBm: unlikely to cause any significant contention issues.

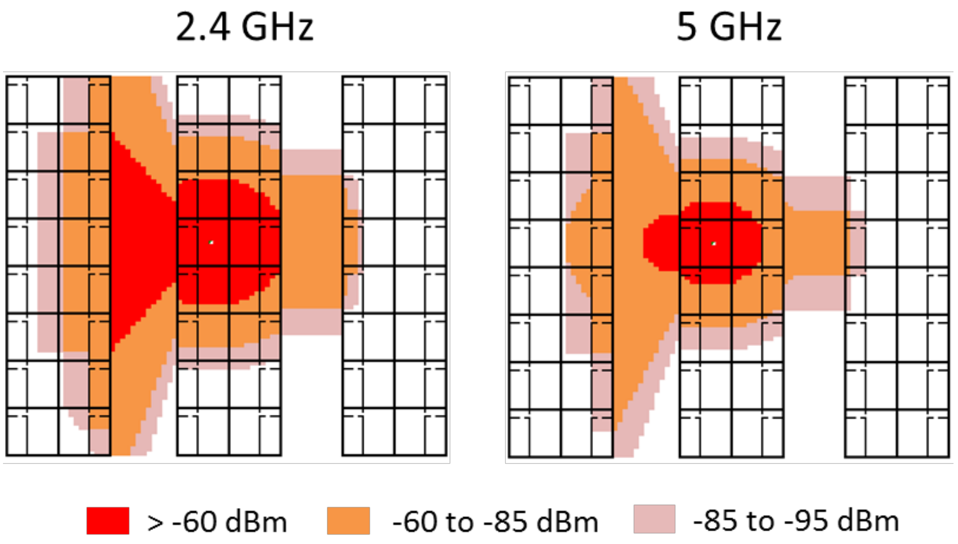
In our modelling we assumed indoor wall separation of 2.5m and free space is assumed for the outdoor area between the residential blocks. The model represents something approaching a worst case scenario for co-existence between neighbouring residential Wi-Fi APs, because of the high access point density and close proximity of the neighbouring access points.

The figure below compares the coverage at 2.4 GHz and 5 GHz, assuming that the same values for wall loss are applied (10 dB).

---

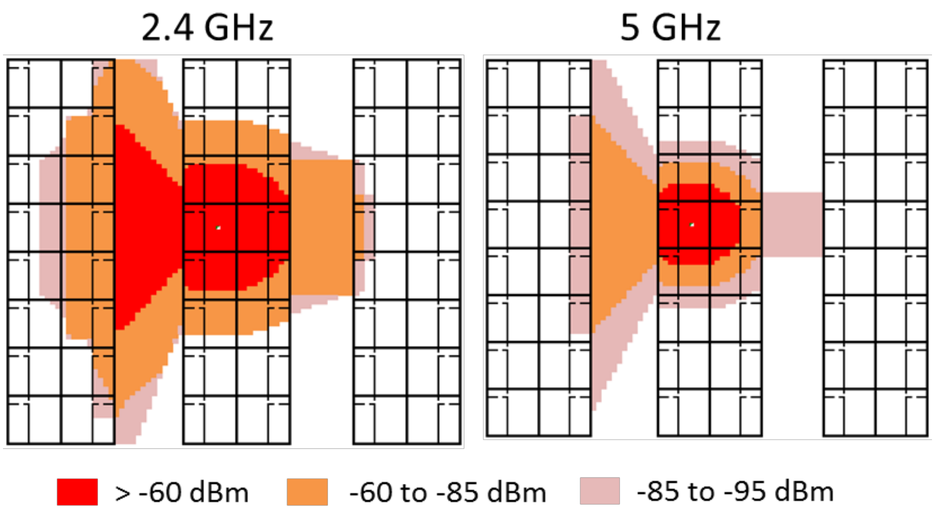
[31] For details see Information Document for SEAMCAT-3 Wiki Help database “SEAMCAT implementation of Extended Hata and Extended Hata-SRD models”

Figure 5-9 Comparison of signal level at 2.4 GHz and 5 GHz (same wall loss assumed)



It can be seen that the 5 GHz signal provides significantly less coverage, although this is still sufficient to cause contention beyond the immediately adjacent property and into the properties immediately opposite, implying that potentially as many as 15 APs might be visible at a given location, leading to a contention ratio of 5 per non-overlapping channel. However, wall loss is in practice likely to be somewhat higher at 5 GHz – for example measurements carried out by Intel[32] indicated typical residential building wall losses of 10.7 dB at 2.4 GHz and 14.9 dB at 5 GHz. Applying these values gives the following results:

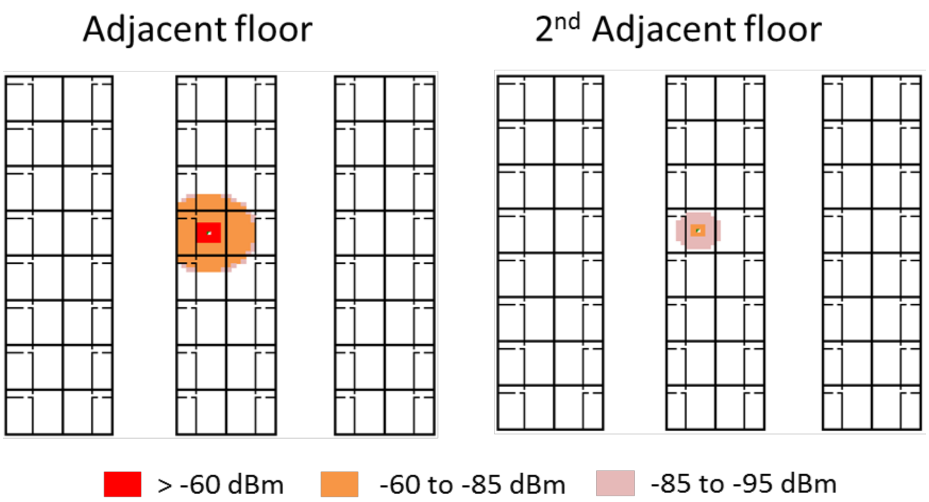
Figure 5-10 Comparison of signal level at 2.4 GHz and 5 GHz (higher wall loss at 5 GHz assumed)



[32] see www.certificationzone.com/cisco/newsletter/SL/nla_12-06-04_wire.html

Note that the contending signal at 5 GHz is now limited to the four immediately adjacent properties, suggesting only 5 APs would be visible at a given location. However, since we are dealing with an apartment block it is necessary to also consider the impact on the adjacent floors. Inter-floor attenuation is likely to be significantly higher than wall attenuation, partly because of the different materials used (typically concrete as opposed to plaster or brick) and partly because the AP antenna gain is generally lower in the vertical direction than horizontal. In the following figure a 30 dB inter-floor loss has been assumed.

Figure 5-11 Projected signal level on adjacent floors (5 GHz)



It can be seen that contention will arise on the immediate adjacent floors, but not beyond that, suggesting the number of visible access points is likely to be at least 7 and potentially as high as 15 if the diagonally adjacent dwellings are also taken into account. However, since 5 GHz APs are generally required to deploy transmitter power control it is likely that typical radiated powers will be lower than the 100 mW assumed here and contention will not generally extend beyond dwellings on the immediate adjacent floors.

5.3.4 Impact of WMAN deployment in a high density residential environment

In a purely residential environment the demand for traffic on a public Wi-Fi network is likely to be considerably lower than in the previous scenario and the number of public hotspots very much fewer. Access could be provided via the residential access points as is already the case with the BT FON network, but this would simply use spare capacity on those APs and not have any implications for spectrum demand. An outdoor network would primarily be required to provide coverage rather than capacity and it is questionable whether the demand in such as location would warrant a dedicated Wi-Fi network. Nevertheless, we have considered the potential impact such a deployment might have if it were to go ahead.

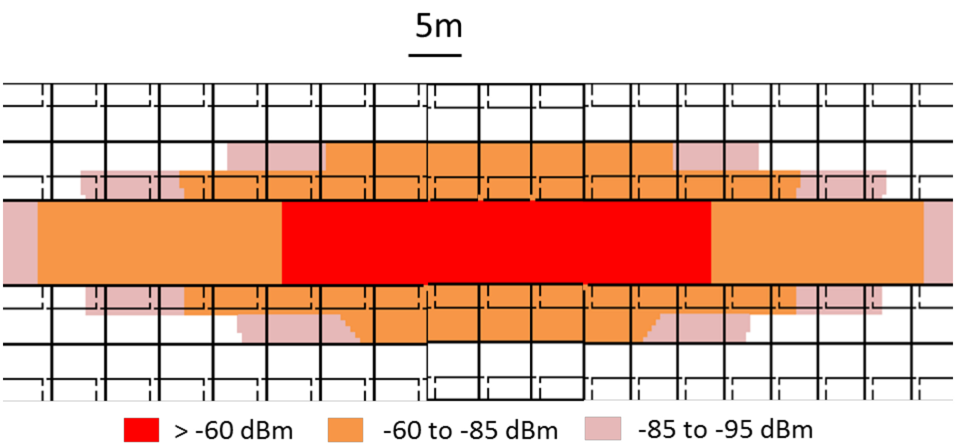
In a street environment, particularly in urban areas, there is likely to be considerable shielding from buildings and the required coverage tends to be linear rather than area based, In such an environment, by deploying beamforming and downtilted antennas to constrain signal spill over to adjacent sectors it should be possible to use as few as two frequencies to provide continuous relatively uncontended coverage in such a situation.

We do not have access to the specific technical characteristics of Wi-Fi networks, so to illustrate this, we monitored the signal level from a typical outdoor access point in central London as a function of the distance from the access point. We found that the signal exceeded -65 dBm for a distance of approximately 30m either side of the access point, then declined steadily to below -85 dBm after a further 30m. With such a configuration, spacing access points at a distance of 60m apart would in principle enable continuous linear uncontended coverage to be provided with as few as two frequencies. In practice, more than two frequencies tend to be used as it is necessary to take account of other local channel usage, especially in the congested 2.4 GHz band.

This concept is illustrated in the figure below, which shows the estimated coverage from an outdoor access point along a residential street with buildings on either side. The orange coverage zone represents the area where contention with a neighbouring AP would be likely. It can be seen that deployment of a second frequency at alternate access points would largely eliminate contention between the outdoor APs. Note however that contention would be significant if the same frequencies were used as in the residential buildings, implying that separate frequencies are required for the indoor and outdoor use in this scenario.

Shielding from the buildings in this scenario would also enable the same frequencies to be re-used in other nearby streets, implying a total spectrum requirement for the outdoor network of two 20 MHz channels, i.e. **40 MHz** in total.

Figure 5-12 Estimated coverage from an outdoor WMAN AP in a dense residential environment



5.3.5 Spectrum requirement for the high density residential scenario

Spectrum demand in this scenario is very much dominated by the residential users. Where relatively small, tightly packed dwellings are involved (as in our modelling here) the scope for spectrum re-use is limited , with an estimated seven access points likely to be visible in a typical residence. The scope for co-ordination or other efficiency boosting measures between residential access points is limited since multiple services providers are likely to be involved and equipment is usually self-installed by end-users. Assuming an uncontended spectrum requirement per household of 40 MHz implies a total requirement for residential users of **280 MHz.**

Additional spectrum to support a single outdoor WMAN, assuming a frequency re-use of 2 could be achieved, would be 2 x 20 = 40 MHz**,** with potentially a further 40 MHz if in-band meshing is deployed. Hence the total spectrum requirement in this scenario is projected to be up to **320 MHz.**

5.3.6 Implications of co-ordination and interworking technologies

The core of the problem with respect to residential networks is that they are not managed in either installation or operation. This immediately limits the prospects of applying co-ordination and interworking methods.

Of the various coordination methods described in Chapter 2, band steering and active channel selection are probably the most likely to be useful. At the moment, with less use of the 5 GHz band, band steering may be quite effective. Over time as traffic increases and users wish to make full use of 802.11ac wide channels, the 5 GHz band may cease to be so capable of supporting such demands. Active channel selection is based on an uncoordinated algorithm. In other words, all access points will select their perception of the best channel independently. A general problem with uncoordinated algorithms is churn, where much swapping of channels may occur, but offering no consistent advantage for any one user.

Interworking technologies like Hotspot 2.0 were not intended for the home market. We are not aware of any current plans to extend into this area, but there appear to be relatively few technical barriers to doing so. Precisely what advantage may be realised is less clear. If it were possible to steer users to their neighbour's AP a boost in efficiency could be conceivable. However the practicality and acceptability of sharing a neighbour's AP and backhaul (from any operator) is questionable without some form of advanced business model. Probably the closest to this at the moment is the BT FON scheme, where bandwidth and backhaul can be shared, but only under the control of a single operator.

We can see that ANDSF, if taken up by the market, could enable automatic switching from cellular to a home network, where each network came either under the control of a single operator or where roaming agreements were in place. The problems with user choice and the role of the device connection manager[33] would still need to be addressed before this became viable.

5.4 Scenario 3: High density business environment

5.4.1 Scenario Description

For this scenario we have again used a modelling approach and have assumed a large, open plan office environment within a dedicated business park or campus. We have considered the potential traffic in such a network and the implications for spectrum demand to support this traffic and provide the required service quality. We have then considered what the impact of deploying one or more outdoor WMANs at the same location might be in terms of co-existence with the business network and for localised spectrum demand.

A key difference between a specialised business environment like this and the mixed environment considered in scenario 1 is that the business use in this case is assumed to be mainly by larger enterprises with extensive corporate data activity rather than the SME use assumed previously. The Wi-Fi networks are therefore likely to be enterprise systems that have been planned and installed professionally with a view to optimising system performance and capacity.

5.4.2 Traffic projections in a high density business environment

There is very little public data relating to the levels of traffic on business Wi-Fi networks. We have already noted (in the context of scenario 1) that the projected national growth rate for business traffic IP traffic is somewhat lower than in the residential environment and current levels of business traffic in total are considerably lower, but we expect that the latter is largely a reflection of the relative size of the two sectors. There were 2.15 million registered enterprises in the UK in 2012 compared to 28 million internet households. Businesses also vary enormously in the extent to which they use data generally and wireless data in particular. Since Wi-Fi spectrum demand is very much driven by local circumstances, simply taking an approach based on average traffic levels is likely to underestimate seriously the traffic demand in the busy locations such as business parks and university campuses. Business users may also place a higher premium on peak data rates to ensure higher performance when accessing cloud based applications (e.g. carrying out data backups or accessing large files).

In view of the lack of data, we have adopted a different approach to this scenario, in that our spectrum estimates for the business use is based on the planning principles typically applied to enterprise networks and consideration of the anticipated local RF environment rather than projected traffic levels.

[33] As we discussed in Chapter 2.

5.4.3 Planning considerations for enterprise WLANs

One of the challenges in planning a network to cater for a high density of enterprise users is that unlike the home environment there is likely to be a large number of users in a relatively small space, often with little in the way of physical shielding between them. A number of access points are likely to be required to meet the required coverage and capacity, but the absence of shielding means that overlap and contention are likely to be more problematic than in the residential scenario where building attenuation tends to limit the range of interfering signals.

Enterprise WLAN designers typically recommend that networks should be configured to connect clients to access points at the highest available data rates possible to maximise application throughput and minimise client airtime utilization[34]. One way to do this would be to deploy wider channels, which would increase the peak data rate and throughput for individual clients (where they are capable of wide-channel operation). However, in a high-density network this may be counter-productive in that it reduces the total number of channels available for reuse among nearby access points, so reducing overall network capacity. In consequence, designers typically recommend a higher density of access points to optimise capacity rather than deploying wider channels.

The argument for this is that in high-density networks, minimising contention and segmenting client devices into separate collision domains is likely to achieve higher overall spectrum efficiency and network performance than deploying wider channel. In other words, having a larger number of uncontended narrower channels (e.g. 20 MHz) is likely to deliver greater overall throughput and spectrum efficiency than a smaller number of wider channels (e.g. 40 or 80 MHz).

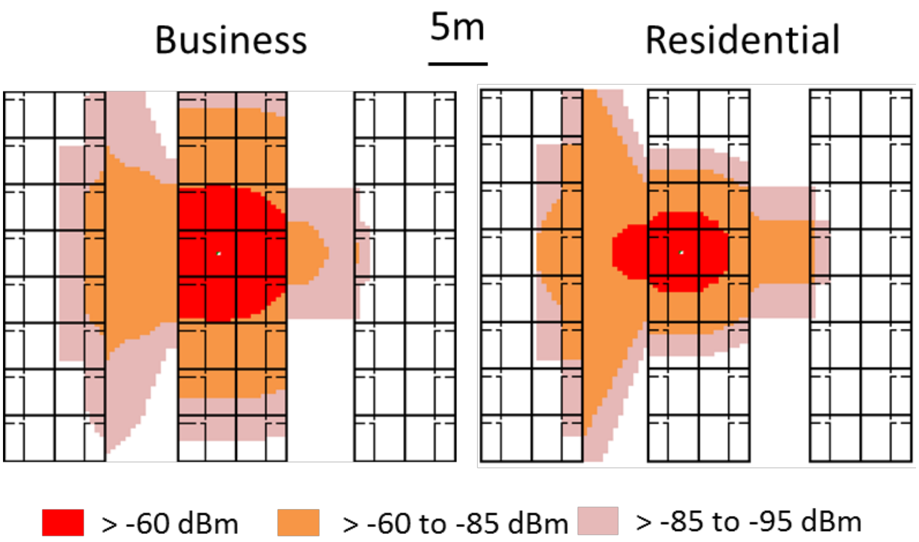
To ensure connectivity at the highest speeds and to avoid contention with other co-channel access points, a minimum signal strength of -65 to -67 dBm with a signal-to-noise ratio of 25-30 dB is recommended. This requires a high density of access points with a good degree of separation between those operating on the same channel, since nearby co-channel access points with signal levels of -85 dB or more are likely to cause medium contention with the wanted access point and capacity and performance will suffer.

A typical open plan business environment with wood or plasterboard partitions but steel or concrete outer wall is likely to have somewhat smaller internal attenuation but greater indoor / outdoor attenuation than the residential environment considered in scenario 2. Actual values will vary considerably between buildings but a typical value at 5 GHz might be 5 dB per internal partition and 30 dB indoor / outdoor attenuation. By comparison, the wall loss value we assumed in the residential environment was 15 dB. Comparing the signal propagation at 5 GHz in the two environments, it can be seen that based on the above assumptions the signal level

[34] See for example "High-Density Wi-Fi Design Principles", Aerohive white paper, 2012

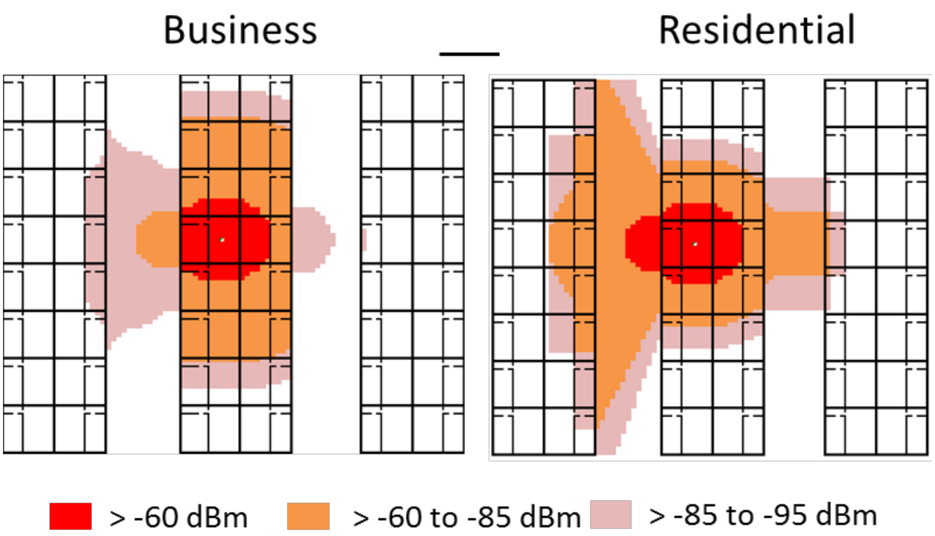
generated by an indoor AP in a business environment extends considerably further indoors, but is lower in the immediate outdoor vicinity to the residential case. Note that in the business case we have assumed that the indoor space is configured into individual work areas 5 m square separated with floor standing partitions having a nominal 5 dB attenuation.

Figure 5-13 Comparison of signal level from an indoor access point in typical business (open plan office) and residential environments



This comparison assumes that the same radiated power applies in both cases, but in practice a lower power would probably be deployed in the business environment, to reflect the lower level of internal attenuation and to reduce contention with neighbouring APs. The impact of reducing the power by 10 dB in the business environment is shown below. Although there is a noticeable reduction in the distance at which contention will occur it can be seen that that contention (represented by the yellow contour) will still arise over a significant area and that contention free operation would require access to 10 or more separate frequencies (more will be required if adjacent floors are also taken into account).

Figure 5-14 Comparison of signal level from an indoor access point in typical business (open plan office) and residential environments, with power reduced by 10 dB in the business environment



Note that this option to reduce AP power also provides enterprise users with another means to expand total network capacity without recourse to more spectrum, so long as sufficient channels exist to ensure individual access points avoid contention with one another.

This implies a potential spectrum requirement of approximately 200 MHz to support traffic in the indoor enterprise network. If outdoor coverage is required, it is likely that a further two 20 MHz channels would be required to provide outdoor coverage (it is assumed that the same considerations as we applied to WMAN networks in the previous scenario would apply to the outdoor business coverage here. A further two channels would be required for in-band meshing of outdoor access points. It is conceivable that some applications, such as CCTV, may require access to additional or wider channels. Given that such applications generally deploy point to point or point to multipoint wireless links with directional antennas, which will tend to enhance spectrum efficiency, we anticipate that this would account for no more than one or two additional 20 MHz channels. Hence the total spectrum requirement for business use would be in the range **200 - 320 MHz**, depending on the nature of any outdoor coverage required**.**

5.4.4 Impact of outdoor WMAN deployment alongside to a high density business environment

The impact of WMAN deployment in a business park of campus setting will depend on the nature of the business Wi-Fi networks that are present. As noted above, some business networks may themselves provide outdoor coverage in addition to indoor, in which case the potential for contention with public WMAN services would be greater. However, outdoor traffic levels would generally be lower than indoor, typically serving mobile devices with more modest data throughput requirements than fixed desktop applications.

In some cases there will also be scope for co-operation between the private and public network providers. Larger corporate networks may for example be managed by operators who also provide public access and in such cases the same hardware and radio resources can be used for both private and public traffic. Examples include BT's "Openzone Guest" facility which enables secure public access over an existing corporate Wi-Fi network, and the Virgin Media London Underground network which also carries private traffic over the same radio infrastructure.

Where the private and public networks are operated by separate providers and there is no co-ordination between the two, contention will arise and may in some instances have an adverse effect on network performance. However, if both networks are configured to seek out optimal RF channels and have access to dual frequency bands it is likely that in most cases this could be avoided, for example by avoiding transmission on frequencies where an existing signal is detected.

In a pessimistic scenario, where the business use required uncontended access to both the outdoor channels (this could arise, for example, if the outdoor network was being used for a high bandwidth application like CCTV), and assuming similar re-use in the WMAN network could be achieved to that in scenario 2, there could be a requirement for up to a further 80 MHz to support an outdoor WMAN (this includes a 40 MHz allowance to support meshing of the access points).

5.4.5 Total spectrum requirement in a high density business environment

Based on the above analysis, the total spectrum requirement in this scenario in the presence of an outdoor WMAN could be as high as **400 MHz.**

5.4.6 Implications of co-ordination and interworking technologies

In contrast to the residential case, the enterprise scenario represents a controlled network. Moreover, in contrast to the WMAN it is also operating in a controlled environment.

Although network management methods are proprietary and actual implementation details are unknown, all the co-ordination methods described in Chapter 2. **.** are available to the enterprise network manager. For example, the 802.11 network extensions, such as 802.11r for VoIP, may be used in a situation where it is known that all clients and APs support the same extensions. It is precisely for the enterprise environment that these extensions were promoted in the 802.11 committee by proponents of enterprise networking.

Because network discovery protocols like Hotspot 2.0 and ANDSF are intended for roaming between public networks, they are less likely to find application within the 'walled gardens' of enterprise networks. Indeed, enterprise network operators may be resistant to devices automatically roaming to other networks. Once again this brings in the future role of the device connection manager and user choice.

5.5 Comparing the scenarios

In the following sections we compare the key characteristics of the three deployment scenarios we have analysed and summarise the estimated Wi-Fi spectrum requirements in each case.

5.5.1 Comparing the traffic mix

The scenarios we have considered are quite different in terms of the nature and volume of traffic likely to be generated. Residential traffic in the future is likely to be increasingly driven by high definition video applications, demanding a high level of continuous bandwidth and limiting the scope for contention between neighbouring access points. There is also limited scope for co-ordination between access points in residential situations, since wireless equipment is usually self-installed and not under direct control of the service provider. Neighbouring dwellings are also likely to have different service providers which are likely to change from time to time.

Business traffic is less likely to be dominated by real-time bandwidth intensive applications like HD video, but increasing reliance on cloud services implies a requirement for high peak bit rates and high capacity at busy times. To achieve this larger enterprise networks typically employ a high density of access points with limited frequency re-use to ensure each access point can operate at the highest rated speed. Optimal network performance and capacity is realised by deploying a larger number of narrower channels rather than a smaller number of wider channels as this results in improved signal to noise ratio and reduced contention across the network. Smaller businesses (such as those found in scenario 1) are more likely to use single access points to meet their requirements, in a similar way to residential users, but traffic levels are likely to be lower (due to less demand for HD video) and a greater degree of contention likely to be acceptable.

Traffic on public Wi-Fi networks is currently considerably lower than on private networks but is expected to grow significantly in the future. This partly reflects the wider growth in mobile data traffic but also a potential increase in offload of traffic from cellular as interworking between the two becomes easier and a growth in Wi-Fi-only wireless devices such as tablet PCs. However, the relatively high density of public Wi-Fi access points in high traffic locations compared to cellular base stations means that, even allowing for this growth, traffic per access point is likely to remain small compared to residential and enterprise networks. In the case of WMANs, traffic per access point may be higher due to the larger area served by the outdoor stations, however deployment of advanced beam steering and channel selection protocols means a considerably better degree of frequency re-use can be achieved on these networks, reducing the overall spectrum requirement.

In summary, residential and enterprise (large business use) appear likely to be the dominant drivers of Wi-Fi bandwidth utilisation in the longer term, with public networks accounting for a growing but still relatively small proportion of overall wireless data traffic.

5.5.2 Estimated spectrum demand in the three scenarios

The table below summarises our estimates of the potential spectrum demand by 2024 in each of the three scenarios we have analysed

Figure 5-15 Summary of spectrum demand estimates

Traffic Type	Scenario 1	Scenario 2	Scenario 3
Residential use	240	280	0
Business use (indoor)	120	0	200
Business use (outdoor)	0	0	120
Public use (indoor)	100	0	0
Public use (outdoor - WMAN)	80	40	40
Meshing of outdoor access points	80	40	40
Total potential spectrum requirement	**620 MHz**	**360 MHz**	**400 MHz**

As one might expect, the demand is highest in the mixed scenario, but this is based on the assumption that additional spectrum will be required to support business use in the mixed residential / business environment. In practice, since the two often have different traffic profiles over the course of the day, it is likely that some contention could take place during the day which would reduce the demand for business use.

Comparing these forecasts with the spectrum that is currently available in the existing Wi-Fi bands (440 MHz in total[35]), we find that in the mixed urban scenario there is a potential 180 MHz shortfall, whereas in the other scenarios there appears to be adequate spectrum to meet the projected demand. However, this assumes that the entire allocated 5 GHz spectrum is available, whereas in practice at some locations some of the channels may be unavailable in order to protect local radar stations.

We also note that the current fragmentation of the 5 GHz band is likely to constrain the extent to which wider channels (80 MHz or 160 MHz) could be deployed under the new 802.11ac standard and would recommend that any additional spectrum to meet the identified shortfall should be ideally be located adjacent to the existing 5 GHz bands to maximise the amount of contiguous spectrum available.

In the following section we consider some of the factors that may impact on traffic and spectrum demand for diffident user types and in the different scenarios we have considered.

[35] Based on nineteen non-overlapping 20 MHz channels at 5 GHz and three at 2.4 GHz (i.e. 380 MHz + 60 MHz)

5.6 Factors likely to influence spectrum demand

We observed in our introduction that there was a high degree of uncertainty in attempting to project future spectrum demand to support Wi-Fi traffic. One of the biggest challenges we faced is estimating the future levels of traffic likely to be carried over Wi-Fi networks in the future. This is in part because of the limited data that is available for existing use and partly because uncertainty over demand growth trends. The uncertainty is particularly great with regard to public Wi-Fi use. Ofcom's own data suggests this is only a very small fraction of cellular mobile traffic, which in turn is only a small fraction of traffic carried over fixed networks.

Traffic offload from mobile networks has been identified by many observers as a major factor in demand growth for Wi-Fi in the future. However, it should be noted that almost all such offload currently is to private home or work networks rather than to public networks (see section 5.2.6.1).

Whist mobile data traffic is undoubtedly growing at a phenomenal rate (Cisco is projecting a 9-fold increase from 2012 to 2017 in the UK, a compound annual growth rate of 54%)[36], network capacity is also set to grow considerably. Current 3G networks have access to 2 x 60 MHz of spectrum in the 2 GHz and 2 x 10 MHz at 900 MHz. When current 2G spectrum and the recently auctioned 800 MHz and 2.6 GHz spectrum is taken into account, this will increase to 2 x 240 MHz and migration to 4G LTE technology will further enhance spectrum efficiency creating greater capacity on the networks. There is growing interest in the deployment of licensed small cells (femtocells) to boost capacity; indeed the latest public Wi-Fi deployments are being configured to allow "hetnet" (combined LTE / Wi-Fi) deployment in the future. All of this creates additional uncertainty about the extent of offload to Wi-Fi in the future.

Our scenario analyses did not explicitly take account of the potential deployment of wider (80 MHz or 160 MHz) channels using the 802.11 ac standard (see section 2.5), since it is unclear at this stage how demand for such use will evolve. Whilst deployment of wider channels is a function that can be managed at network level in a large enterprise network (such as we have considered in scenario 3), in a high density mixed or residential environment it is likely that reliable deployment of wider 802.11ac channels would be challenging, due to the presence of large numbers of unco-ordinated residential access points operating on narrower channels across the available band. This may create a longer term demand for additional spectrum to support the wider 802.11ac channels.

On a more general note, it should be noted that our projections are based on anticipated traffic levels in 2024 and that continuing long term growth in wireless data traffic beyond that date may also create demand for additional spectrum.

[36] VNI Mobile Forecast Highlights, 2012 - 2017

6 CONCLUSIONS

In this study, we were asked to review the extent to which the likely future evolution and deployment of Wi-Fi technology would affect spectrum utilisation, with a particular focus on co-ordination, interworking and roaming. Our findings suggest that the impact of enhanced access point co-ordination on overall spectrum demand is likely to be small. This is largely because such enhancements are unlikely to be adopted to any significant extent in the residential market, which in the long term we expect to dominate demand for Wi-Fi spectrum. Even in enterprise networks, the scope for substantial improvements in spectrum efficiency is limited, albeit to a lesser extent, due to the need to support a wide mix of client devices, via the BYOD[37] effect. Although enhancements such as 802.11k are being adopted in the latest generation of public WMAN deployments, the industry perception is that any benefits will be limited due to the inconsistent way that these enhancements are likely to be adopted by device vendors..

A more promising development in terms of improving spectrum efficiency is the wider deployment of beamforming techniques to provide better targeted coverage, improved signal quality (and hence throughput) and reduced contention between nearby access points. Vendors claim that this can provide substantial benefits in WMAN and enterprise deployments, with one vendor suggesting an overall throughput improvement of as much as 70% is feasible. It is unclear however what assumptions underpin this estimate, for example whether such gains would be realisable in a heavily loaded radio environment or where multiple networks are co-located.

Dynamic channel management protocols, such as Ruckus' ChannelFly, have also been adopted in a number of WMAN deployments to enhance performance and capacity, particularly in the congested 2.4 GHz band. According to Ruckus, such techniques have the potential to boost capacity by as much as 25 – 50 % in congested RF environments, but again it is unclear what assumptions have been made in arriving at this estimate.

In general we caution that the deployment of unmanaged optimisation methods such as beamforming and dynamic channel assignment may be open to unintended consequences with respect to their operation in some dense, mixed, multi-operator environments. This is because there is, in general, no guarantee that independent optimisations will lead to a stable network level optimisation. However it is perfectly conceivable that specific future work could dispel concerns in this area.

[37] The Bring Your Own Device effect means that the enterprise network, which was previously a well defined walled garden, now increasingly has to cope with an influx of a range of user devices, including not only clients but potentially users' APs via for example mobile Wi-Fi hotspots or Wi-Fi Direct™.

In terms of future demand, it is clear that there is much uncertainty surrounding the level of traffic that might be carried over Wi-Fi networks in the future. This is particularly the case for public Wi-Fi networks (hotspots and WMANs), although it seems likely from our analysis that such traffic will remain relatively small compared to that carried over residential and larger enterprise networks. Interworking advances (such as Hotspot 2.0) may however lead to substantially increased demand (albeit from a very low base), but will also have the capability to help this demand be handled more efficiently by networks in the future.

Other technology enhancements may have less impact on traffic demand. For example, there is an issue over who owns the end user, which means the 3GPP backed ANDSF initiative may fail because there will be resistance to its operation from end users and device manufacturers. The WFA's Hotspot 2.0 does not really suffer from this in the same way.

Other technology enhancements still suffer uncertainties with respect to their effect on demand. Several aspects of Wi-Fi operation remain implementation independent including the device connection manger. A possible implication is that the 3GPP backed ANDSF initiative may not succeed in the market because there will be resistance to its operation from end users and device manufacturers. This is due to conflicts over end user ownership, for example when user, mobile operator and Wi-Fi operator connection preferences and policies conflict. The connection manager also leads to 'sticky' handover behaviour in some implementations. New standards work is just beginning in this area, within the Open Mobile Alliance (OMA) and the IETF, which we have suggested that Ofcom follows.

We also suggest that Ofcom follows the very recent proposal to create an IEEE 802.11 High Efficiency study group, which is expected to address the issues of high density WLAN deployments and may include the additional considerations of multi-operator environments.