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To White Space Or Not To White Space: That Is The Trial Within The Ofcom TV White Spaces Pilot

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***Abstract*—TV White Space (TVWS) has taken a big step forward with the UK regulator Ofcom initiating a pilot of the technology in the UK, based on rules for White Space Devices (WSDs) standardized and harmonized at the European level by ETSI. This paper reports on a subset of the work undertaken by our large-scale trial within the Ofcom Pilot, investigating what is achievable in TVWS in terms of availability and capacity, and strongly focusing on the potential to aggregate white space resources. Moreover, this paper provides some experimental results and observations from our trial, particularly around issues such as performance testing and assessment of appropriate scenarios for TVWS deployments.**

Some of the key observations in this paper, among numerous others, include:

(i) In the UK, it seems likely that TVWS has most performance/benefit potential in below-rooftop receiver and indoor/underground deployments. For availability and capacity analyses, we particularly define and assess TVWS scenarios that we term as "mobile broadband downlink" and "indoor wireless local-area networking" based on this realization. We further demonstrate the strength of TVWS for indoor communications through a range of challenging experiments inside the Strand Campus of King's College London.

(ii) There is ample TVWS available in much of the UK and particularly in the London area, although this is affected greatly by the scenario that is considered and can be very highly variable. The mobile broadband downlink scenario is particularly affected by availability reduction and variability outside of the London area. Impressive capacities can be achieved by optimal aggregation in TVWS. Achievable area capacity in TVWS is high.

(iii) In a number of cases, and particularly under some aggregation scenarios, subsets or indeed all WSD spectrum mask classes give similar performance.

(iv) A worst case 700 MHz spectrum reassignment for ITU Region 1 in WRC 2015 could significantly affect availability/capacity in some TVWS usage scenarios, for lower quality spectrum mask class WSDs.

Keywords*—*TV white space, geolocation databases, field trials, spectrum aggregation, spectrum sharing

I. INTRODUCTION

Progress in TV White Spaces (TVWS) has been propelled forward initially by regulatory steps and deployments of White Space Devices (WSDs) in the US [1], [2]. In addition to white space trials and developments elsewhere such as in Africa and Asia, Europe is proceeding with the finalization of rules and testing of TVWS technology on a large scale [3]-[6]. The European progress is particularly driven by the UK regulator Ofcom's work and instantiation of a large pilot of WSDs and the underlying enabling technology [6]. All trials within this pilot must operate under Ofcom's prospective rules for WSDs, reflected in ETSI EN 301 598 [5].

The Ofcom Pilot serves purposes and objectives such as:

- Provision of a proof of concept of the TVWS framework.
- Verification before commercial TVWS operations start.
- Involvement of the regulator, industry, and end users in the process, such that their individual roles and interactions between the relevant stakeholders can be verified.

The Ofcom Pilot also aims to test several aspects, such as:

- WSD operation and conformance.
- Geolocation database (GLDB) contract qualification.
- GLDB operation and calculations.
- Ofcom's provision of the qualifying GLDB listing.
- Ofcom's Digital Terrestrial Television (DTT) calculation results and provision of Programme Making and Special Events (PMSE) data.
- Interference management.
- Coexistence.

In practice, this further includes verification of aspects such as the testing methodology for WSD RF performances, the testing methodology for WSDs interactions with Ofcom's "database of GLDBs" and selection of the appropriate GLDB to use, the testing methodology for WSD interactions with the GLDB (including aspects such as security), and the testing methodology for correct operation of WSDs (e.g., RF channel/power settings based on information from the GLDB, ceasing to transmit when communication with the GLDB is not successfully carried out, and changing of RF channels and powers if necessary, based on changed information from the GLDB). In essence, it also includes the methodology for monitoring interference and the correctness of interference levels around deployments of WSDs, the assessment of any possible effects on primary services, and verification of security precautions, among other aspects. The correct performance of all of these elements is essential to the assurance of the viability of the wider picture of TVWS, and the confidence that the regulator is able to authorize this technology for commercial use under its rules.

Our trial within the Ofcom Pilot is the subject of this paper. Further, this paper particularly emphasizes work on analysis of what is available in TVWS in the UK (in terms of available number of channels) and what is achievable in TVWS (in terms of performance, capacity) through aggregation of TVWS resource. It also touches on the implications of methodologies for aggregation in TVWS.

This paper is structured as follows. The utilized WSDs, locations and deployment scenarios are outlined in Section II. Section III presents some early results from our trial from the point of view of practical deployments, and some important observations derived from those results for TVWS in the UK. Section IV presents some results of our availability and capacity analyses, particularly emphasising aggregation approaches. Finally, Section V concludes this paper.

II. TV White Space Devices, Deployment Locations and Scenarios

Our trial has amassed a wide range of WSDs for use over various durations. These cover a number of radio interfaces, both proprietary, and adhering to standards such as IEEE 802.11af and 3GPP LTE (the latter with extensions for TVWS). More information on these devices is available in [7], [8]. However, for the purpose of this paper, the vast majority of our work is done using Carlson RuralConnect WSDs [9], as well as an implementation of the logical control aspect of a WSD (including communication with the Ofcom weblisting of GLDBs, and communication with the Fairspectrum GLDB) prepared by King's College London and providing a part of the implementation of the Eurecom ExpressMIMO2 software radios to operate as WSDs [10]. The Carlson RuralConnect devices, used in this paper for the link testing cases, operate with a Coded OFDM (COFDM) waveform, with modulations 16-QAM, QPSK or BPSK, and with coding schemes of no coding, ¾-rate convolutional coding, or ½-rate convolutional coding. The modulation and coding can be either manually set, or automatically selected by these devices.

Regarding trial locations and given our trial being driven by academics and research institutes, a large number of University campuses have been made available for usage as part of the trial. More information on these is available in [7], [8]. However, for the purpose of the work reported in this paper, the following locations were used:

- Locations at King's College London campuses in London, including the Strand, Waterloo, Guys (London Bridge), and Denmark Hill.
- Queen Mary University of London (Mile End Campus, East London).

In this particular paper, rooftop sites at King's College London Denmark Hill, Guys (London Bridge) and Queen Mary University of London Mile End Campus have been used to investigate relatively large-area provisioning and provisioning of long-distance point-to-point links. Moreover, experimentation and long-term provisioning of indoor broadband services in TVWS has been undertaken at King's College London's Strand Campus. Extensive work is also reported in this paper assessing white space availability and capacity across London and a wide area of England, through the use of our aforementioned WSD logical implementation to query databases, and rigorous processing of the results.

Regarding the scenarios our trial is considering, detailed information on these is again available in [7], [8]. However, this particular paper reports some of our results and observations linked to the following cases:

- Experimentation with long-distance point-to-point links in TVWS. Example applications of this include long-distance backhaul provisioning, and emergency and Public Protection and Disaster Relief (PPDR) provisioning. This topic particularly links to some important observations on scenarios for WSD usage, as well as observations on the UK TVWS framework in general.
- Linked to our observations derived from such work, very detailed analyses of the use of WSDs for scenarios we term as:
    - Mobile broadband downlink.
    - Indoor wireless local-area networking.

  Moreover, this comprises the extensive consideration of potentials for such cases, e.g., the capacity achievable by optimally aggregating TVWS resources non-contiguously and contiguously, and the effects of WRC 2015 on white space availability and capacity, among other aspects.
- Extensive experimentation on the use of WSDs for indoor broadband provisioning, e.g., to provide backhaul to difficult to reach rooms and locations, or to provide backhaul in emergency and PPDR scenarios.

III. Some Early Results and Observations

Our trial has run, in various phases of work, from June 2014. A number of observations and results from our trial are reported in this Section.

A. *Scenarios for TV White Space Usage*

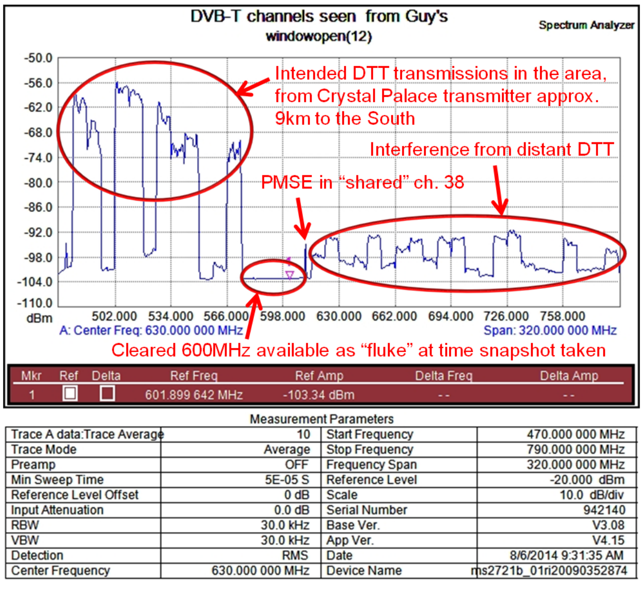
One initial observation arising from our long-distance point-to-point link testing, referring to Fig. 1, has been that the busy nature of TV bands usage in London points to some particular applications as being most useful for TVWS. In scenarios where the WSDs are placed high above rooftops, interference has been experienced towards WSDs, originating, for example, from distant primary (e.g., DTT) transmitters that are not meant to be covering the area. This is the case even for the many locations and channels at which WSDs are allowed to operate with maximum Equivalent Isotropic Radiated Power (EIRP) according to the Ofcom/ETSI framework. Given knowledge about the spatial TV channel usage mapping applied across the UK, it is anticipated that a similar situation exists across much of the UK, and particularly in areas where there is an overlap, or at the boundary, of TV broadcast station coverage areas.

This has implications for the viability of TVWS scenarios where WSD receivers are placed high above rooftops aiming to receive a very low-power signal. For example, our 7 km point-to-point long-distance backhaul link between King's College London Denmark Hill and Queen Mary University of London Mile End Campus has been affected significantly by this issue, with the interference from distant primary DTT stations (even in the many channels that the WSDs are allowed maximum EIRP on) effectively reducing the received SINR from a viable/useable value (of typically slightly less than 10 dB) by an order of magnitude to negative dB values or lower. This emphasizes that it is highly important to scan the spectrum for the best channel to use, based on the interference situation in channels, before choosing a channel. It is noted that some WSDs already support that. Indeed, our trial has observed that for this long-distance backhaul link case, it is far better to use an alternative channel that is allowed lower than maximum EIRP (in this case, TV channel 37, allowed 31 dBm—5 dB lower than the maximum EIRP according to the framework) than TV channels that are allowed a maximum EIRP of 36 dBm (e.g., channel 48) in the GLDB response.

Based on such observations, we infer that TVWS in the London area and likely across much of the UK is most interesting in below roof-top receive radio cases (e.g., downlink provisioning), or cases where propagation characteristics at TV frequencies can be used to greatly improve coverage in challenging cases, such as inside buildings and metro systems, for example.

B. *WSD Parameter Values and Parameter Acquisition*

Another key observation of our trial relates to the procedures for WSDs obtaining parameters, and the values of those parameters that are obtained. The Ofcom/ETSI framework specifies the concepts of master and slave devices, and specific and generic WSD operational parameters. The slave devices must obtain parameters via a master device, first forwarding their characteristics to the master device such that the master device can query the database on their behalf. The master device must transmit initial allowed parameters that any slave device can use anywhere within the coverage area of the master, such that the slave is able use those parameters to transmit its characteristics to the master. Parameters that allow this initial, "inspecific" transmission by slave devices are termed "generic" slave parameters, and parameters that are based on the later-obtained precise information from slave devices are termed "specific" slave parameters. An issue is that, given that generic slave parameters are effectively the worst case allowed power for any possible location within the master coverage area, their allowed powers are typically extremely low—so low as to not be usable even for the purpose of initial link formation. For example, in the challenging case of King's Strand Campus, for a master WSD transmitting at 31 dBm, the generic slave EIRP is lower than 3 dBm in all channels. This EIRP is not sufficient for the slave to transmit information to the master and the link be formed.



Mkr	Ref	Delta	Ref Freq	Ref Amp	Delta Freq	Delta Amp
1	☐	☐	601.899 642 MHz	-103.34 dBm	- -	- -

Measurement Parameters

Trace A data:Trace Average	10	Start Frequency	470.000 000 MHz
Trace Mode	Average	Stop Frequency	790.000 000 MHz
Preamp	OFF	Frequency Span	320.000 000 MHz
Min Sweep Time	5E-05 S	Reference Level	-20.000 dBm
Reference Level Offset	0 dB	Scale	10.0 dB/div
Input Attenuation	0.0 dB	Serial Number	942140
RBW	30.0 kHz	Base Ver.	V3.08
VBW	30.0 kHz	App Ver.	V4.15
Detection	RMS	Date	8/6/2014 9:31:35 AM
Center Frequency	630.000 000 MHz	Device Name	ms2721b_01ri20090352874

Fig. 1. A spectrum survey performed looking South from the King's College London Guys Campus hospital tower, clearly showing the intended TV transmissions covering the area, interference from distant DTT transmissions that are not meant to be covering the area, and other characteristics such as a PMSE device transmitting on the shared PMSE channel 38.

C. *WSD Performance Assessments*

Next addressing results on the performance of WSDs and white space in general, first assessed are the long-distance links between King's College London Denmark Hill and Queen Mary University of London Mile End Campus (7 km distance), and King's College London Denmark Hill and King's College London Guys at London Bridge (3.7 km distance). In both cases, channel 37 was used, for which the maximum allowed EIRP returned by the GLDB was 31 dBm. This choice was because of aforementioned issues concerning interference to the WSDs from DTT, even on channels on which the absolute maximum EIRP of 36 dBm was allowed. It is noted that the former 7 km link was only just able to be formed. Although there is optimization that could be done on that link, the best rate that could be achieved was around 60 kbps over 7 km, and the least challenging modulation and coding (BPSK with ½-rate convolutional coding) could only achieve a BER of around 1-2%. The best-case SINRs achieved were in the range of 8-10 dB. The 3.7 km link enjoyed far better performance, where 16-QAM ½-rate convolutional coding achieved a BER of 10^{-6}. Lab testing implies this leads to a downlink rate of 6.4 Mbps, and uplink rate of 5.1 Mbps.

Another area of performance assessment has been for indoor broadband provisioning, e.g., providing indoor point-to-point backhaul for broadband access points. This assessment has been done at the Strand Campus of King's College London, which is valuable for such as effort given its wide range of building types and implementable scenarios. Fig. 2 depicts the layout of the parts of the Strand and King's buildings in the Strand Campus considered in this work. Five links are considered in this paper. Link 1 is from the "Flexible Radio" lab of the Centre for Telecommunications Research at King's College London to the first author's office, on the same floor and through some 4-5 walls including a closed metal blind covering a high-loss glass wall at the author's office. The distance of the direct path for Link 1 is approximately 10 m. Link 2 is from the lab to the "Old Committee Room" in the King's Building, some 20 m away over a partial change in floor level, noting that the King's Building is of very rugged stone construction. Link 3 is across some 90 m in the King's Building, although mostly guided along a corridor, with a partial change in floor level close to the white space base station location. Link 4 is across numerous rooms/walls to the “Refectory”, some 80 m away on the same side of the King’s building as the other end-point of the link, thereby giving potential to use external reflections to improve link performance. Link 5 is to a classroom on the second floor of the Strand Building, transmitting diagonally up through at least 3 walls/floors, and across by some 10 m.

Initial results are in terms of the performance for various modulation and coding rates, using the Carlson RuralConnect WSDs. Before any tests were done, a first assessment was the achievable performance for a (near-)ideal link, through transmission in the same room between the base station and terminal, with antennas directed away from each other and attenuated by 19 dB to ensure that the received signal didn’t experience compression/saturation due to a high signal level. The SINR observed by the receive radio in this case was 34.8 dB. We assessed this link for a number of minutes, using the highest rate modulation (16-QAM) and no coding. In the entire duration that the link was assessed, not a single bit (hence packet) error occurred.

First testing Link 1, the performance for 16-QAM with no coding or with ¾-rate coding was already excellent. No other modes were tested as it was found that the WSDs already performed sufficiently in these most challenging modes of operation. Moreover, for Link 1, the WSDs anyway defaulted to 16-QAM with no coding if configured to automatically select modulation and coding scheme. It is not known what algorithm the Carlson devices use for automatic modulation and coding selection, however, it is expected that they broadly use a scheme such as to make this selection based on received SINR, and adapt if the SINR moves into a different range on average, for more than a certain duration of time. Moreover, it is noted that the radios of the devices operated at an output of 20 dBm, the feeder cable loss was 1 dB, and the antenna gain was 11 dB. This gave an EIRP from the setup of 30 dBm. The devices were set to use TV channel 37, noting that only channels 27 and 37 were viable for Carlson Class 3 WSD usage at the Strand. For the location/height at the Strand that the work was done, the GLDB allowed a maximum power of 31 dBm for both these channels.

Referring to the 16-QAM with no coding case, the average BER was $2.7*10^{-3}$. The average packet success probability (assuming a packet size of 1.5 kB) was 95%. With ¾-rate convolutional coding applied, the average BER was reduced to $1.2*10^{-3}$, and the average packet success probability was increased to over 99%. Moreover, the rate that the Link achieved, with the devices operating in automatic modulation and coding selection mode and the link being stress-tested using a number of speed testing tools, was in the range of 6.5-8.3 Mbps on the downlink, and 2.6-3.2 Mbps on the uplink. It is noted that a radio-firmware update has been made available for the Carlson devices, which has been applied and the rates tested again using this. It is believed that this firmware improves the digital processing of the signal to make it flatter in the frequency domain. The firmware update improved the downlink rate to somewhere in the range of 10.0-11.5 Mbps; the uplink rate was unchanged.

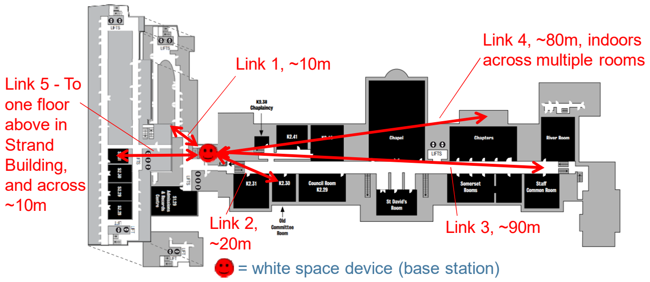


Fig. 2. Indoor plans of the Strand and King’s buildings (combined) of the King’s College London Strand Campus. The Strand Building is to the left of the WSD, and the King’s Building is to the right. Both the 1st and 2nd floors of the Strand Building are depicted, whereas only the 2nd floor of the King’s Building is depicted.

Moving on to Links 2-4, Link 2 achieved a performance of in the range of 5.7-9.9 Mbps on the downlink, and 1.0-2.2 Mbps on the uplink. It is noted that the high range of achieved rates was due to the link falling back from 16-QAM with no coding to 16-QAM with ¾- or ½-rate convolutional coding both on the downlink and uplink during the testing. Interestingly, in coding/modulation testing, 16-QAM with no coding achieved a bit error rate of $1.1*10^{-8}$ and a packet success probability of 99.98% (to two decimal places) again assuming a packet size of 1.5 kB. For reasons of such good performance with the most challenging modulation and coding scheme, further testing of modulation and coding schemes that were less challenging for this link was not done. Further, it was observed that the high variability in performance was due to activity in the building hence attenuation by students and staff, noting that the initial modulation/coding link testing that demonstrated excellent performance was done in August when the building was almost empty, whereas the later link rate stress-testing was done in October when the building was extremely busy and there was a high variability of students and staff using the corridors/rooms. This ranged from the corridors/rooms being almost empty to being extremely busy often changing within the timescale of a few minutes.

Regarding Link 3, performance was highly variable depending on the number of people in the vicinity, and particularly the number of people there were in the 2nd floor corridor of the King’s building. It was noted that in a busy scenario, the link could already achieve a BER of between 10^{-3} and 10^{-4} in QPSK and no coding, and if any coding was added then the BER became 10^{-5} or better. In terms of packet error rate, this was observed to be less than 1%. Lab testing indicates that these values would imply an achieved rate (using TCP transport) for the devices of very approximately 4 Mbps on the downlink, and 1 Mbps on the uplink.

Regarding Link 4, the performance of this link was extremely variable depending on the placing and orientation of antennas at each end of the link, noting that we only used orientations where the antenna was pointed directly towards the receive radio, or varied by a maximum of 90° to that. For example, with BPSK modulation and no coding, by optimising the antenna position and origination at each end of the link the bit error rate could be reduced from approximately $5*10^{-2}$ to approximately $2*10^{-6}$, more than a factor of 10,000. It is noted that through varying antenna positions on this link, it was possible to achieve good performance even with 16-QAM modulation and no coding. This is reflected in the rates that were achieved testing the devices, in the range of 1.1-9.8 Mbps on the downlink, and 0.1-1.2 Mbps on the uplink.

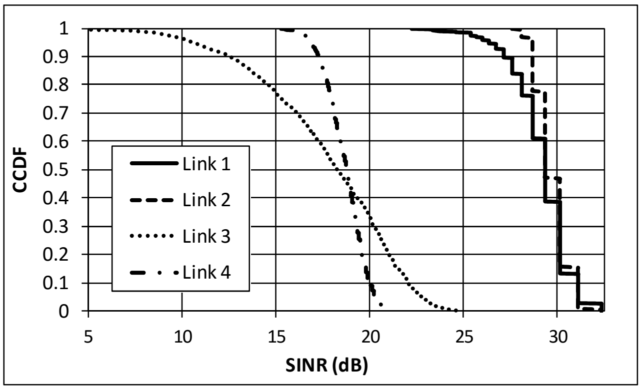


Fig. 3. CCDFs of received SINRs for Links 1-4.

Finally, Link 5 achieved a near-perfect performance. The observed SINR on the downlink was 29.4 dB, and the observed SINR on the uplink was 31.2 dB. Noting that testing was done using the new firmware for the devices, the achieved downlink rate was in the range 10.9-11.6 Mbps. The uplink achieved rate was in the range 1.7-2.3 Mbps.

On a separate occasion, we have assessed the SINR distributions (CCDFs) achievable for Links 1 to 4 (see Fig. 3). Based on this assessment, Link 1 exhibited a high variability with SINR of at least 25 dB, although in this case that was due to variations in people in the building and around the antenna; more typically, the SINR for Link 1 was in the range of 28-31 dB. Link 2 showed a low variability, with SINR in the range of 27-31 dB. Link 3, largely guided by the long corridor in the King's Building, showed an immense variability depending on the number of people in the corridor, SINR being typically of at least 7 dB but in some cases over approximately 23 dB. Link 4, in this case using a typical but non-optimized antenna configuration, showed a far more stable but somewhat low SINR of at least 16 dB.

D. *Coexistence with Primary Services*

Various experiments concerning coexistence testing with primary DTT and PMSE services are being done within our trial. The key objective is to assess interference to primary services caused by power leakage into adjacent channels, with a WSD transmitting at maximum allowed power in the adjacent channel and performance of the primary service being recorded or otherwise statistically assessed. We have used the most geometrically challenging deployment configurations that it is possible to envisage in attempting to cause interference to the primary services, e.g., with the WSD antenna and TV receive antenna mounted on the same pole 10cm apart for DTT interference assessment. Some initial results and more detail are in [8]; the key observation is that it has thus far not been possible to cause any observable interference to DTT or PMSE primary services.

IV. WHITE SPACE AVAILABIITY, CAPACITY AND AGGREGATION STUDIES

Key questions are: How much white space is there, and what can be achieved using that white space? These are all the more important to answer for the UK case, which operates under significantly different rules from the US.

TABLE I: SCENARIO CONFIGURATIONS

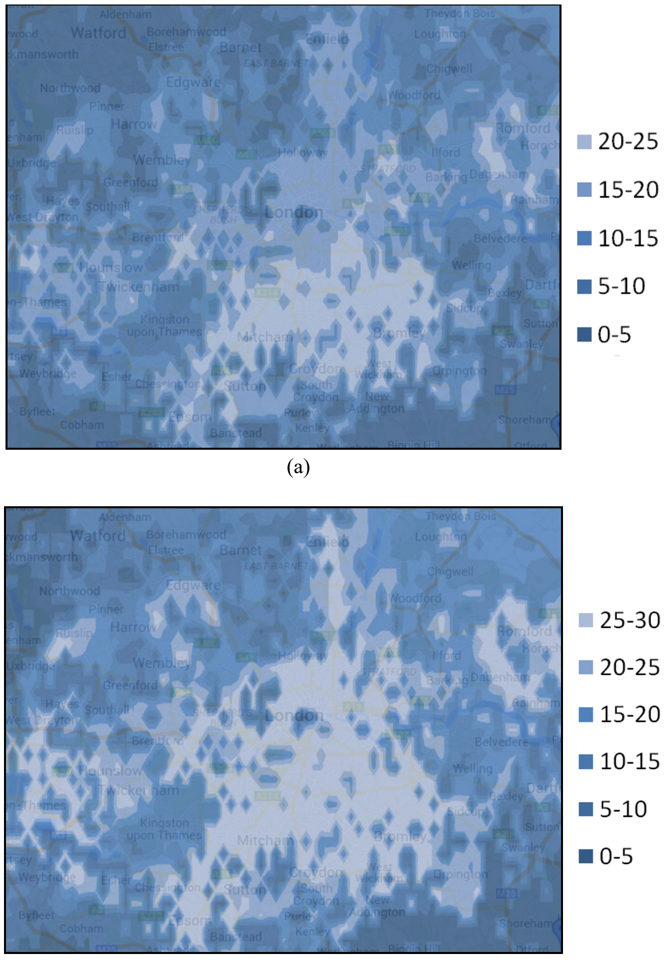
Scenario	Transmitter Height (m)	Receiver Height (m)	Transmission Distance (m)	Path loss	Shannon Efficiency
Mobile Broadband Downlink	30	1.5	2,000	Hata Urban, large city	0.5
Indoor Wireless Local Area Networking	1	1	80	Yamada model, 8 walls, same floor, King's College Strand parameters [11]	0.5

Fig. 4. The investigated London M25 area for availability, capacity and aggregation studies.

To shed some light on this, we have investigated the available white space in the London, UK area, and also the optimum capacity that can be achieved by aggregating all of that white space. Our studies have sampled white space availability according to the UK framework in a rectangular lattice defined by the top-left corner (latitude, longitude) 51.678064, -0.506744, and the bottom-right corner 51.312133, 0.229340, with a sampling frequency of 0.01° both in latitude and longitude. This equates to the area approximately as bounded by the London M25 orbital motorway/highway, and 2,775 sampled locations within that area. Fig. 4 maps the considered area. Further, for comparison, this work has been extended and reported later in Section IV.D to consider a much larger area of England.

We have adapted one of our implementations of the WSD-side logical requirements to methodically query Fairspectrum and obtain information on available white space, and do capacity analyses with a particular emphasis on aggregation scenarios. This work is based on the implementation of the Ofcom Framework as was the case in January 2015.

We study two scenarios for the purpose of our availability and capacity analyses, which we term the "mobile broadband downlink" scenario and the "indoor wireless local-area networking" scenario. The mobile broadband downlink scenario is inspired by the realization that above-rooftop reception can be hampered by interference from distant DTT transmissions that are not meant to be covering the area, as reported in Section IV, and it is likely that other WSD transmissions will also cause interference in such deployment cases going into the future. This scenario is further inspired by the efforts that are being made towards the realization of LTE supplemental downlink scenarios albeit initially in the form of



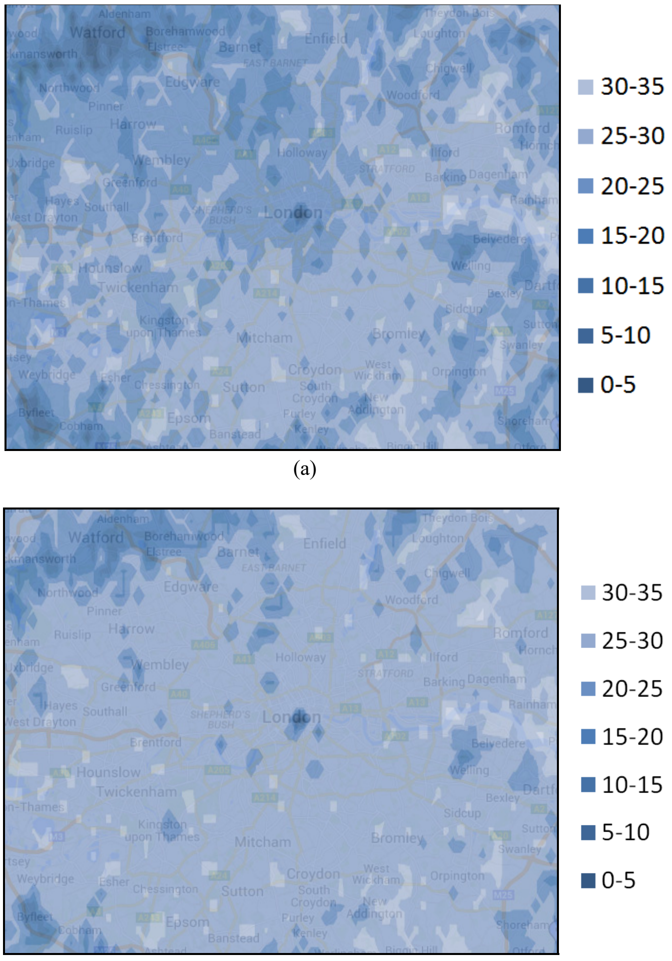
(a)

(b)

Fig. 5. Number of "usable" channels available for the mobile broadband downlink scenario: (a) Class 5 device, (b) Class 1 device.

LAA unlicensed access in 5GHz U-NII spectrum. Given this, the downlink can typically be observed to experience far less interference than the uplink in TVWS, whereby TVWS can be a facilitator for enhancing capacity, conveniently being located extremely close to the LTE 700 and LTE 800 spectrum thereby facilitating design of LTE devices should they wish to use TVWS for a supplemental downlink. The "indoor wireless local-area networking" scenario is inspired by the fact that TVWS channels will be much "cleaner" indoors, and indoor propagation is far better in TV bands than other bands used by WLANs such as ISM 2.4 GHz and U-NII 5 GHz.

The characteristics of these scenarios are given in Table I. Note that the transmitter height is one of the parameters used by the white space database (in addition, of course, to location and other parameters such as the spectrum mask class) in assessing allowed powers on a per-channel basis, whereas the receiver height is used merely for propagation loss calculations, and the assumed Shannon efficiency of the radio interface is for capacity calculations. Moreover, propagation characteristics are purposefully set to be extremely challenging for the given scenarios, whereby the mobile broadband downlink scenario uses the most challenging



(a)

(b)

Fig. 6. Number of "usable" channels available for the indoor wireless local-area networking scenario: (a) Class 5 device, (b) Class 1 device.

TABLE II: STATISTICS ON NUMBER OF "USABLE" CHANNELS AVAILABLE FOR THE MOBILE BROADBAND DOWNLINK SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

	Number of channels				
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	15.6	15.4	15.2	12.6	10.2
STD	8.4	8.4	8.5	8.1	7.1
CoV	0.54	0.55	0.56	0.64	0.70

TABLE III: STATISTICS ON NUMBER OF "USABLE" CHANNELS AVAILABLE FOR THE INDOOR WIRELSES LOCAL-AREA NETWORKING SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

	Number of channels				
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	25.7	25.6	25.5	24.9	23.4
STD	3.4	3.4	3.6	4.2	5.2
CoV	0.13	0.13	0.14	0.17	0.22

variant on the Hata propagation model over a propagation distance of 2 km. The indoor wireless local-area networking scenario uses a propagation model that was developed at King's College London for indoor TVWS transmissions, and parameterized at the Strand building of King's College London [11]. Particularly for this scenario and parameterization, this propagation model has been shown to perform far better than any available alternatives [11]. The transmission is over a distance of 80 m indoors and through 8 walls. It is noted that the extremely challenging nature of these characteristics mean that results in this case can be seen as something of a worst case in terms of capacity analysis.

A. Number of Channels available

Fig. 5(a) maps the number of channels that are available for the mobile broadband downlink scenario (assuming a minimum allowed EIRP of 30 dBm), over the London M25 area corresponding to that presented in Fig. 4, for a Class 5 device. Fig. 5(b) presents the equivalent for a Class 1 device, and Table II gives statistics over the area for all classes of devices. Fig. 6 and Table III present the same results for the indoor wireless local-area networking scenario, which assumes that a minimum allowed EIRP of 20 dBm is acceptable in assessing channel availability.

One first clear observation from these results is that Classes 1-3 are very similar in terms of availability, with availability only starting to significantly reduce for Classes 4 and 5. Moreover, it is noted that there is a very good correlation of availability with (i) the location of the London TV transmitter at Crystal Palace (marked in Fig. 4), and (ii) the building density in the area. Considering (i), this is because there is one TV transmitter providing sole coverage in the area hence not other TV transmitters blocking out different sets of channels to achieve their multiplexes thereby reducing white space availability, noting that in the UK the different TV transmitters use different frequencies in order to avoid interfering with the reception of each other (content transmitted by the different transmitters can also vary significantly among the various transmitters and regions). Considering (ii), this is because of the increased propagation loss in built-up areas, thereby allowing greater availability/EIRP for WSDs in those areas. Comparing with areas such as the north-west and south-west of the assessed location, availability is reduced significantly because of the overlap of TV transmitter coverage for those areas, and the reduced propagation loss. An extreme case is presented for the Guildford location discussed later in Fig. 9, whereby there is severe overlap of various TV transmitters, and availability is reduced significantly.

Another observation is that there are a large number of relatively small "spots" of reduced availability. These are caused by PMSE (e.g., wireless microphone) deployments, noting that PMSE is also licensed and deployment locations recorded in the UK, hence is protected to the same level as TV broadcast services. The most severe such location is part of the "West End" area of London, incidentally coinciding with the South Aldwych/Strand area and the King's College London Strand Campus, covered extensively in later discussion. This is the area about a quarter of the way down and on the right side of the letter "d" of "London" in Figs. 4-8. This reduced availability is due to PMSE usage of numerous nearby musical theatres, concert halls, TV production, among others facilities.

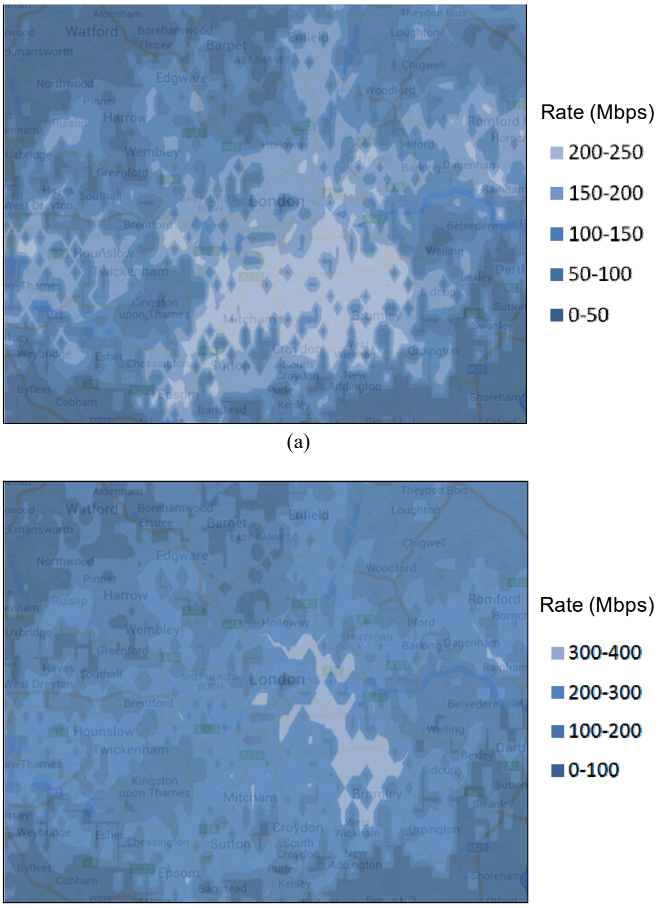
Concerning statistics on availability reflected in Tables II and III, it is noted that for the mobile broadband downlink scenario an average of approximately 10 to 15 channels is available depending on class; the coefficient of variation (CoV) of this number increases somewhat from 0.54 to 0.70 as the spectrum mask performance class is reduced. For the indoor wireless local-area networking scenario, an average of approximately 23 to 26 channels are available, with a coefficient of variation increasing from 0.13 to 0.22 as the spectrum mask class quality is reduced. Hence, the indoor wireless local-area networking scenario achieves both greater availability on average, and better certainty in the availability of spectrum. There is somewhat of a reduction in such availability as the transmitter height is increased, however, that is not significant. Moreover, it is noted that the reduced EIRP requirement for the indoor wireless local-area networking scenario is the key cause of the greater certainty, leading to a reduced number of locations for which PMSE and TV primary services impact on the allowed EIRP enough to violate the 20 dBm threshold.

A further observation is that a worsening of spectrum mask class has a far more severe effect for the mobile broadband downlink scenario, as compared with the indoor wireless local-area networking scenario. This conveniently matches with the observation that white space base station deployments for the mobile broadband downlink scenario will be relatively sparse, and be able to absorb a greater expense in achieving a good spectrum mask class. Radio deployments for the indoor wireless local-area networking scenario will be very dense indeed, and typically done only by the consumer/end-user. Expense for such cases must be minimized, which seems to be viable given that deployment of a Class 5 device, for example, seems to in most cases have a relatively small effect on performance as compared with Class 1.

B. Achievable Capacity

Next assessed are the achievable capacities for the mobile broadband downlink and indoor wireless local-area networking scenarios. In all cases, a capacity calculation is done based on the allowed EIRPs in all channels, assuming the "optimal" aggregation of all channels at maximum allowed EIRP on a per-channel basis. As indicated previously, challenging propagation characteristics are assumed (see Table I), leading to what might be seen as a "worst case" for achievable capacity.

Achieved aggregate capacity mapped to the locations in the London M25 area for the mobile broadcast downlink scenario is given in Fig. 7, and for the indoor wireless local-area networking scenario in Fig. 8. Corresponding tables of statistics are in Tables IV and V. It is noted that many of the same observations as are made in the analysis of available number of channels apply. However, there are some differences. For example, more of a negative effect is observed if the spectrum mask class is reduced from Class 2 to Class 3 for the mobile broadband downlink scenario. This is because there are reduced EIRPs for Class 3 devices, hence reducing the capacity that is achievable by aggregating channels at maximum allowed EIRP, however, these reduced



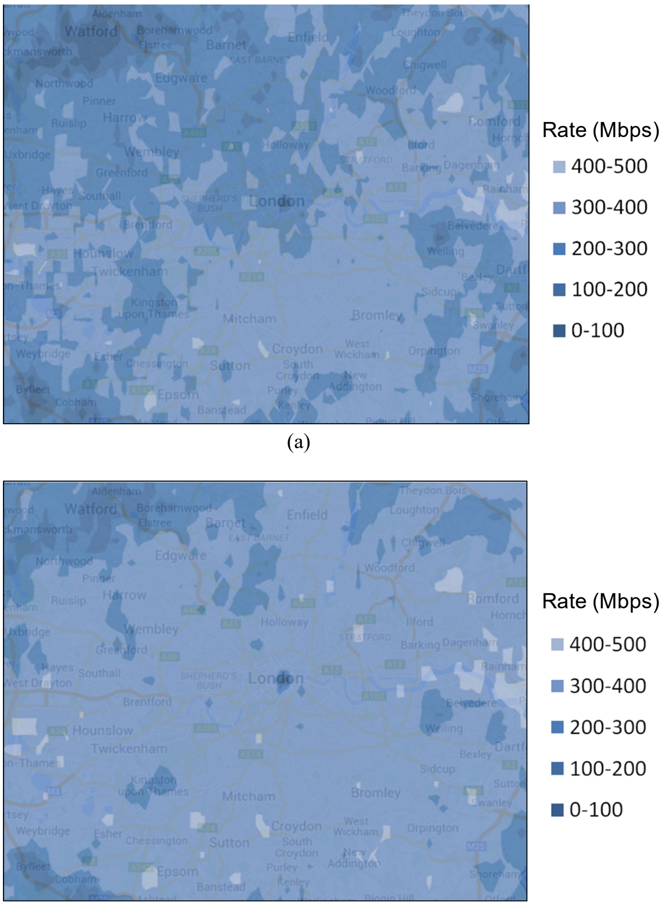
(a)

(b)

Fig. 7. Capacity achievable by optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis for the mobile broadband downlink scneario: (a) Class 5 device, (b) Class 1 device.

EIRPs rarely fall below the threshold of 30 dBm to rule the channels as "not available" under this scenario as we define it.

Extending observations from the analysis of the number of channels available, Class 1 and Class 2 performances remain almost identical, both in terms of average number of channels and capacity and in terms of variability of those, although in the case of the analysis of the capacity achieved Class 3 performances are reduced somewhat. This leads to the conclusion that, given a relatively "noisy" design of WSD, there would be little benefit gained by striving for the more challenging -79 and -84 dB requirements in further-out channels than the adjacent channel, if the device already achieved -74 dB in the adjacent hence other channels. Moreover, it is noted that the -74 dB requirement in the Ofcom UK/EU case is equivalent to -55 dB in the FCC US case, due to the Adjacent Frequency Leakage Radio (AFLR) being measured for 100 kHz "chunks" in adjacent channels as compared with the 8 MHz value in the intended channel under the UK model. Hence, AFLR is already automatically 19 dB (80x) lower in a like-for-like power spectral density comparison. Devices developed and already meeting emissions requirements for the US case would therefore be classified as Class 2 or better under the UK case.



(a)

(b)

Fig. 8. Capacity achievable by optimally aggregating all available channels at maximum allowed EIRP on a per-channel basis for the indoor wireless local-area networking scneario: (a) Class 5 device, (b) Class 1 device.

TABLE IV: STATISTICS ON ACHIEVED BATE BY OPTIMALLY AGGREGATING ALL AVAILABLE CHANNELS AT MAXIMUM ALLOWED EIRP ON A PER-CHANNEL BASIS FOR THE MOBILE BROADBAND DOWNLINK SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	167.0	165.1	155.4	130.9	104.7
STD	84.2	84.4	82.5	77.4	66.8
CoV	0.50	0.51	0.53	0.59	0.64

TABLE V: STATISTICS ON ACHIEVED BATE BY OPTIMALLY AGGREGATING ALL AVAILABLE CHANNELS AT MAXIMUM ALLOWED EIRP ON A PER-CHANNEL BASIS FOR THE INDOOR WIRELESS LOCAL-AREA NETWORKING SCENARIO, FOR ALL DEVICE SPECTRUM MASK PERFORMANCE CLASSES

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	333.5	330.9	327.5	312.5	285.6
STD	54.9	55.6	58.8	65.4	67.9
CoV	0.16	0.17	0.18	0.21	0.24

1) *Aggregation Options*

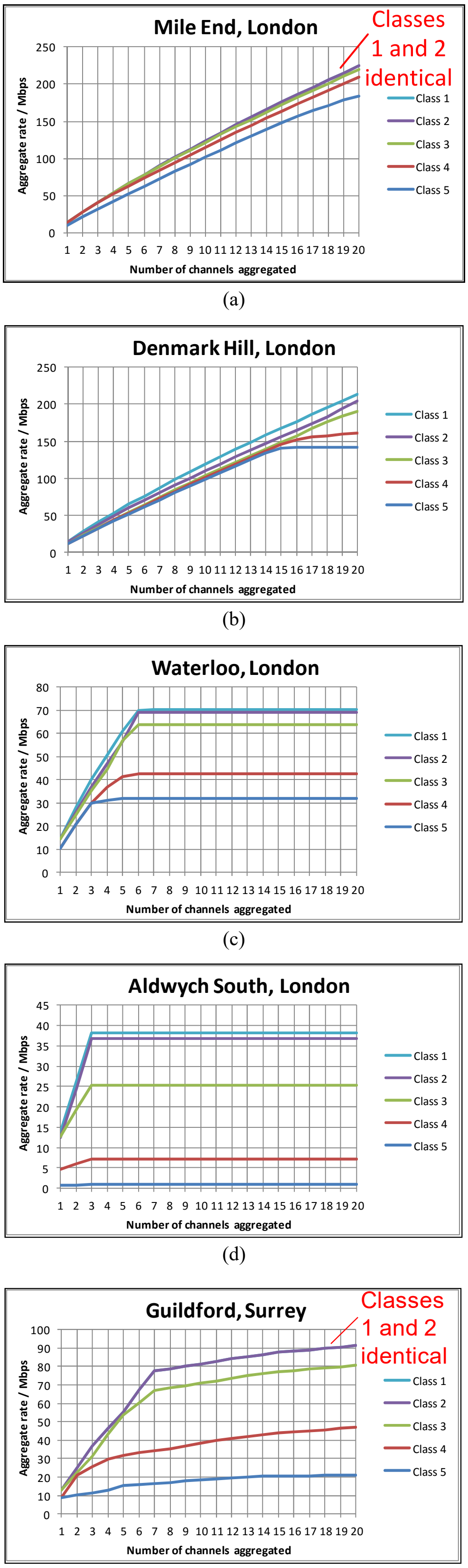
Next assessed is the performance that is achieved through implementing various aggregation configurations in TV white space. Fig. 9 presents the achieved capacity for the mobile broadband downlink scenario against the number of channels that are aggregated for a small subset of the locations that we are taking advantage of for deployments in our trial. Fig. 9 assumes either contiguous or non-contiguous aggregation (i.e., that the radio can take advantage of all channels optimally with maximum allowed EIRP on a per-channel basis, no matter how they are distributed across the frequency band). This could be seen as feasible, for example, under an advanced radio interface such as filter-bank multi-carrier that is able to "notch out" certain channels and still use those available ones at precisely the power limit. A very simple channel selection rule ascertains the next available channel to use:

1. Choose the channel with maximum allowed EIRP according to the UK framework.
    a. If EIRP is equal among the next available channels (note, this is common under the UK framework, as EIRPs are given as integer dBm values), choose the channel of equal EIRP with the lowest frequency.

Results for the non-contiguous cases in Fig. 9 are presented progressively in the order of the most favorable to the least favorable for aggregation (or, indeed, often for white spaces usage in general). Considering the results for Mile End, in Fig. 9(a), this is the best location for white spaces usage among those assessed. Performance increases almost linearly with the number of channels that are aggregated, with a slight drop-off in performance for worse performance spectrum mask classes due to increased adjacent channel leakages, either (i) ruling out some lower frequency channels at equal power for aggregation, meaning that higher-frequency (worse propagation/performance) channels have to be used at equal power, or (ii) in some rare cases causing a reduction in the allowed power in order to maintain adjacent channel leakage requirements.

For the Denmark Hill case, it is possible to observe the start of cases where the limit on the number of channels that can be used for aggregation is hit, for worse spectrum mask classes, due to the adjacent channel leakage requirements. Class 4 performance here represents a worsening of the phenomena seen for Mile End case under poorer performance classes, whereas the "flat-lining" of the Class 5 case indicates that the limit has been hit. The Waterloo and South Aldwych cases show the situation where a large number of channels are ruled out due to extensive PMSE usage in the area, the South Aldwych case being perhaps the most severely affected in the whole country. Moreover, it is noted that PMSE usage is the cause of the relatively-abrupt flat-lining for the Denmark Hill case observed.

The Guildford case here represents what is seen when the limitations are largely due to DTT, Guildford white space being severely affected by overlapping DTT transmitter coverages transmitting multiplexes at different frequencies. This DTT limitation on white space usage leads to a reduction



(a)
(b)
(c)
(d)
(e)

Fig. 9. Capacity achievable by optimally aggregating different numbers of channels at maximum allowed EIRP on a per-channel basis for the mobile broadband downlink scneario, at some specific locations.

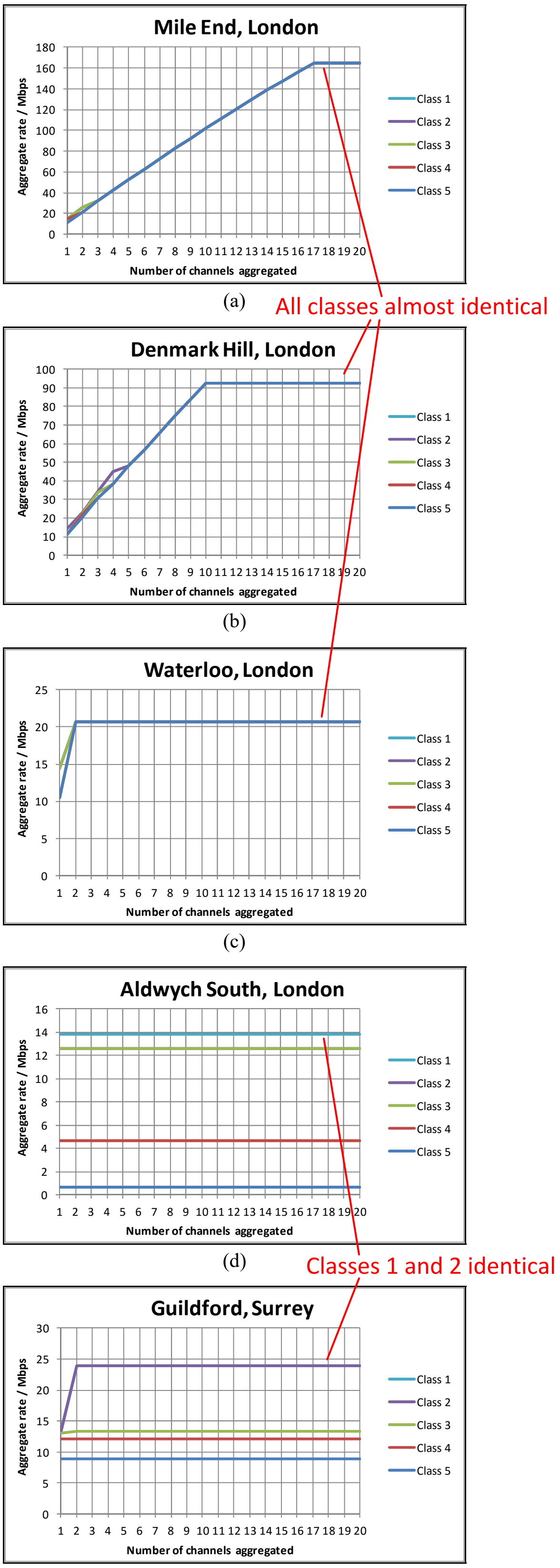
in EIRPs on many channels, but not the flat-lining that PMSE usage leads to as has been observed for the South Aldwych, Waterloo, and somewhat the Denmark Hill locations.

A further observation from these results is that, again, Classes 1 and 2 lead to very similar performance, if not identical performance. Particularly in cases where potential interference victims are more than a certain distance away (e.g., in the Guildford case) the performance is identical. This is because at more than a certain (very short) distance, the -79 and -84 dB down limitations for further-out channels than the adjacent channels no longer have an effect, as received power at the victim receivers has already dropped below the level at which unacceptable interference is caused without the need for those additional limitations.

Fig. 10 represents the case where the WSD can only aggregate contiguous channels, e.g., should it have only one radio that can transmit contiguously which is of variable bandwidth. Under this case, the following algorithm has been used for choosing channels and powers:

1. For all possible sets of *n* contiguous channels.
    a. Ascertain the EIRP of the lowest allowed among the contiguous channels.
        i. Transmit on all of the contiguous channels with this equal lowest power, even if some of the contiguous channels support higher allowed power. This is necessary in order to not violate regulatory limits on a per-channel basis, assuming that the radio produces a relatively “flat” waveform over the allowed channels.
2. Perform the same operation as in Step 1 for *n*-1, *n*-2, etc., to *n*=1 contiguous channels.
3. Take the result of the highest rate among all possible sets of contiguous channels assessed in Steps 1 and Step 2 above as the achieved value for *n* contiguous channels.

One key initial observations is that except for rare examples (e.g., Guildford), Class doesn’t have a major effect on capacity achievable. This has profound implications for the design of WSDs: there is, in a number of cases, little to be gained by striving for higher performance classes than Class 5, given the significant RF expense/complexity that that implies. For example, a manufacturer might concentrate on designing a device with the maximum ability to aggregate contiguous channels (bandwidth), even if that design affects performance somewhat in terms of adjacent channel leakage (which might often be the case if bandwidth is being increased) thereby reducing the spectrum mask class. However, such an observation depends on the required guarantee of service for the white spaces system, as in some cases, particularly where there are a small number of dispersed channels available (e.g., the Aldwych South case) or cases where multiple TV transmitters are overlapping, the out-of-channel emissions can infringe on the primary services more under the algorithm above, hence class playing a more important role. Generally, an overriding observation is that, as the number of contiguous



(a)

(b)

(c)

(d)

(e)

Fig. 10. Capacity achievable by aggregating different numbers of contiguous-only channels for the mobile broadband downlink scneario, at some specific locations.

TABLE VI: STATISTICS ON WORST CASE WHITE SPACE AVAILABILITY AFTER WRC 2015 FOR THE MOBILE BROADBAND DOWNLINK SCENARIO.

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	8.5	8.4	8.1	5.6	3.6
STD	5.0	5.0	5.1	4.6	3.5
CoV	0.58	0.60	0.62	0.82	0.96

TABLE VII: STATISTICS ON WORST CASE ACHIEVED AGGREGATE CAPACITY AFTER WRC 2015 FOR THE MOBILE BROADBAND DOWNLINK SCENARIO.

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	102.2	100.4	90.8	67.4	43.7
STD	53.0	53.4	51.5	46.3	34.0
CoV	0.52	0.53	0.57	0.69	0.78

TABLE VIII: STATISTICS ON WORST CASE WHITE SPACE AVAILABILITY AFTER WRC 2015 FOR THE INDOOR WIRELESS LOCAL-AREA NETWORKING SCENARIO.

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	14.1	14.1	14.0	13.3	12.0
STD	2.6	2.7	2.8	3.4	4.2
CoV	0.19	0.19	0.20	0.26	0.35

TABLE IX: STATISTICS ON WORST CASE ACHIEVED AGGREGATE CAPACITY AFTER WRC 2015 FOR THE INDOOR WIRELESS LOCAL-AREA NETWORKING SCENARIO.

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	165.4	163.0	160.0	146.2	121.5
STD	36.8	37.6	40.3	45.2	43.4
CoV	0.22	0.23	0.25	0.31	0.36

channels available to aggregate increases, distance to primary victim receivers quickly becomes the limiting factor rather than the out-of-channel emissions, rendering class to be of lesser or no importance.

C. Will WRC 2015 Kill TV White Space?

A penultimate availability/capacity study done here is to assess the effect that WRC 2015 (to take place in November 2015) would have in a worst case scenario. At WRC 2015, the final rules and lower bound for the allocation of ~694-790 MHz to mobile broadband on a co-primary basis will be decided. Should all of that spectrum be taken by mobile broadband in all locations, the effect would be that channels 49-60 would not be available for TV white spaces usage. In this section, we therefore perform a further study on available channels and achievable capacity if channels 49 and above are ruled out. Exactly the same prior assumptions, parameterizations, and investigated London M25 area apply.

Results under this assumption are presented in Tables VI and VII for the mobile broadband downlink scenario, and Tables VIII and IX for the indoor wireless local-area networking scenario. One key observation is that, for the mobile broadband downlink scenario, the effect—particularly for lower classes of RF performance—could be severe. In particular, it is noted that even in some London suburb areas (not considering other further-out/challenging cases, such as the previously-discussed Guildford case) large parts of the area, particularly in the North-West and South-West suburbs, have zero channel availability with allowed power of over 30 dBm. Further, there is a significant increase in the uncertainty in the availability of both channels and achievable capacity for the mobile broadband downlink scenario.

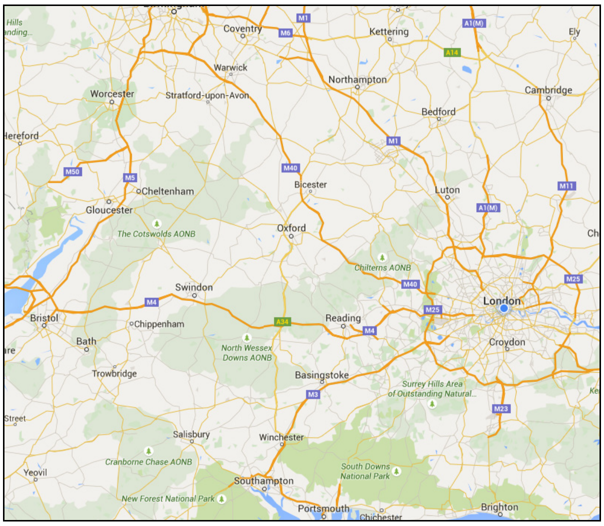


Fig. 11. The investigated wider area of England for the availiablity and capacity comparison studies reported in Tables X-XIII.

Under the indoor wireless local-area networking scenario, the effect is less severe. However, there is a reduction in both the number of available channels and achievable capacity as would be expected. The effect on the variability of availability/capacity is also less severe although is noticeable.

Regarding these results, the worst-case nature of them cannot be overemphasized. For example, in addition to the worst case lower bound consideration (which could perhaps, for international compatibility reasons, indeed result in the current assumption of 694 MHz carrying through) there are uncertainties as to whether WSD usage would remain allowed in this co-primary band, and if it were allowed, the extent to which access would be taken up by mobile operators and the resulting availability of white space in this band.

D. The (Slightly) Bigger Picture

Finally, we have succeeded in identifying a much larger area of England supported by the Ofcom framework and our utilized GLDB. We use this to perform a similar assessment to Sections IV.A and IV.B, sampled at a resolution of 0.05 degrees in latitude and longitude. Fig. 11 maps this area.

The results in Tables X to XIII reinforce our assessment of the white spaces situation in the UK. However, they emphasize a greater variability than our assessment for the London M25 area, particularly for the mobile broadband downlink scenario. This limits its stability for poorer mask classes, also being reflected in the capacity that can be achieved. Further, although space limitations prevent showing results, the availability and capacity are shown to be very high in a large area between Bedford and Cambridge, coinciding well with the location of the Sandy Heath TV transmitter. This supports our assertion that TV transmitter coverage area overlaps correspond to drops in white space availability.

TABLE X: WIDE-AREA STATISTICS ON WHITE SPACE AVAILABILITY FOR THE MOBILE BROADBAND DOWNLINK SCENARIO.

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	8.9	8.8	8.5	6.6	4.4
STD	7.2	7.2	7.2	6.6	5.7
CoV	0.81	0.82	0.84	0.99	1.29

TABLE XI: WIDE-AREA STATISTICS ON AGGREGATE CAPACITY FOR THE MOBILE BROADBAND DOWNLINK SCENARIO.

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	106.4	103.4	98.5	78.9	57.0
STD	74.6	72.0	71.5	66.0	58.1
CoV	0.70	0.70	0.73	0.84	1.02

TABLE XII: WIDE-AREA STATISTICS ON WHITE SPACE AVAILABILITY FOR THE INDOOR WIRELESS LOCAL-AREA NETWORKING SCENARIO.

Number of channels

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	26.5	26.5	26.4	25.8	24.4
STD	5.9	5.9	6.1	6.7	7.9
CoV	0.22	0.22	0.23	0.26	0.32

TABLE XIII: WIDE-AREA STATISTICS ON AGGREGATE CAPACITY FOR THE INDOOR WIRELESS LOCAL-AREA NETWORKING SCENARIO.

Achieved Rate (Mbps)

	Class 1	Class 2	Class 3	Class 4	Class 5
Average	315.3	307.1	306.6	288.9	259.7
STD	88.0	86.2	90.4	96.9	108.2
CoV	0.28	0.28	0.29	0.34	0.42

V. CONCLUSION AND IMPORTANT FUTURE-PROOFING OBSERVATIONS

The Ofcom TV White Spaces (TVWS) Pilot represents an important milestone in the realization of TVWS technology. This paper has described a subset of the work in a trial that is being undertaken under this pilot by an extensive consortium. It has detailed some initial results that have been obtained, concentrating very extensively on the availability and capacity that is achieved in TV white space scenarios termed as "mobile broadband downlink" and "indoor wireless local-area networking", derived particularly from our observations on some of the most useful scenarios for TVWS. Another key emphasis is on what can be achieved by aggregating resources in TVWS, and analysis of some basic means for aggregating resource. Further, this paper has discussed performance assessments of white space devices in a number of scenarios including long-distance outdoor point-to-point transmissions, and indoor transmissions.

Importantly, Ofcom has in February 2015 issued a statement approving of TVWS usage in the UK by license-exempt devices operating under the developed geolocation database-based framework [12]. However, that same statement outlines some planned refinements to the framework, which for the most part can be read as a tightening up of protection (allowed interference reductions in dB) for primary DTT and PMSE services. This will, in many cases, lead to a reduction in the allowed EIRPs of white space devices. Although this implies a reduction in white space availability and capacity, it is anticipated that the broad observations provided in this paper will remain the same. Moreover, it is noted that in adopting these higher protection levels for the roll-out of license-exempt white space devices, Ofcom is deliberately being extremely conservative. It is our understanding that Ofcom is further planning to adapt such assumptions (likely progressively reducing their severity—to something closer to the conditions when the work was done in this paper) as long as interference is not occurring in the commercial roll-out of white space technology and devices. Ofcom also aims to improve the situation through better modelling of aspects such as propagation in TVWS, thereby allowing increased EIRPs.

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REFERENCES

[1] FCC, "In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band, Second Memorandum, Opinion and Order," September 2010.

[2] FCC, "In the Matter of Unlicensed Operation in the TV Broadcast Bands, Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band, Third Memorandum, Opinion and Order," April 2012.

[3] Ofcom, "TV white spaces - A consultation on white space device requirements," consultation, November 2012.

[4] Ofcom, "TV white spaces - approach to coexistence," consultation, September 2013 (an addendum to this from November 2013 also exists).

[5] ETSI, "White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive," v1.1.1, April 2014.

[6] Ofcom TV White Spaces Pilot, http://stakeholders.ofcom.org.uk/spectrum/tv-white-spaces/white-spaces-pilot, accessed May 2014.

[7] O. Holland, et. al., "A Series of Trials in the UK as part of the Ofcom TV White Spaces Pilot," IEEE CCS 2014, Rhine River, Germany, September 2014.

[8] O. Holland, et al., "Some Initial Results and Observations from a Series of Trials within the Ofcom TV White Spaces Pilot," IEEE VTC 2015-Spring, Glasgow, UK, May 2015.

[9] Carlson Wireless RuralConnect, http://www.carlsonwireless.com/ruralconnect, accessed May 2014.

[10] Eurecom ExpressMIMO2, http://www.openairinterface.org/expressmimo2, accessed May 2014.

[11] W. Yamada, …, O. Holland, et al., "Indoor Propagation Model for TV White Space," CROWNCOM 2014, Oulu, Finland, June 2014.

[12] Ofcom, "Implementing TV White Spaces," statement, February 2015, accessible at http://stakeholders.ofcom.org.uk/consultations/white-space-coexistence/statement, accessed May 2015.