On Using White Space Spectrum

William Webb,

ABSTRACT

Use of the "white spaces" in the UHF TV band has been identified as an important spectrum resource, providing new unlicensed spectrum access in frequency bands with excellent propagation characteristics. As a result, regulators around the world have been working on technical measures that will allow the use of this spectrum without interfering with incumbent licensed users. Defining these measures is complex and can have major implications on the amount of white space actually available. This article looks at a number of aspects of defining, using and regulating white space and shows which parameters are critical. It compares regulatory approaches put forward in the UK and US and demonstrates how the current US approach results in much restricted spectrum access. It also assesses key factors for the technologies using white space and shows how all these factors influence the applications most likely to succeed.

INTRODUCTION

It has long been known that much of the licensed spectrum is under-utilized, with spectrum being available in certain geographies or at certain times. This spectrum has been termed "white space" (because it appears white, or uncolored, on some coverage maps) and there has been much discussion and research as to how it might best be accessed. Attention has focused on the UHF bands used for TV broadcasting because they have favorable propagation characteristics and the existing usage is relatively static and readily characterized. However, the principles of white space access can be extended to any frequency bands. The preferred mechanism for accessing white space is through a geolocation database where devices report their location to a database which returns channels available at that location [1, 2].

In determining whether white space can be used there are two factors to consider:

- Whether unlicensed use will interfere with licensed users in the band (and hence should not be allowed).
- Whether licensed use will degrade the white space or render it unusable.

This article explores these two factors in some detail, showing their impact on the use of white space and device performance levels. This article focuses on the TV UHF white space spectrum by way of illustration, although the analysis can be readily extended to other bands by substituting relevant licensed device parameters for that band.

Throughout the rest of the analysis we will refer to the unlicensed use, users and devices as TV white space (TVWS) use, users and devices, respectively.

Also, in the TV bands, the analysis focuses on interference to TV receivers. There are other important users of these TV bands, such as wireless microphones, which also need protection, but this has much less of an impact on TVWS availability than TV usage because:

- The "coverage area" of a wireless microphone system is much smaller than that of a TV transmitter.
- Much of the wireless microphone use is in "safe harbor" channels, which are not available for white space operation.

Hence, in deriving statistics and implications for white space use, wireless microphones operation can be omitted as an approximation. However, in any actual database implementation this is not the case — as careful a consideration must be given to avoiding any interference with wireless microphone receivers as to TV receivers.

INTERFERENCE WITH LICENSED USERS

Interference with licensed users can occur via two mechanisms:

- Emissions from TVWS users that fall into the band used by licensed users. These are typically out-of-band emissions from TVWS devices that fall in-band for the licensed device.
- Emissions from TVWS users that are outside of the band used by the licensed user, but which the licensed user's device is unable to filter adequately and hence results in interference. These are typically the in-band emissions from the TVWS device that fall in channels close to that used by the licensed device.

In practice, a combination of these two will occur. For example, a TVWS device operating two channels away from a TV receiver might cause interference as a result of its out-of-band emissions at n+2 channels (where n is the channel the TVWS device is operating on). Simultaneously it might cause interference as a result of its in-band emissions being poorly filtered by a

0163-6804/11/$25.00 © 2011 IEEE

TV receiver with limited rejection at two-channel separation. Which of these is most significant will depend on the relative performance of the transmit filters in the TVWS device and the receiver filter in the TV (or other licensed device). For a given device location, if a geolocation database providing access to the white space spectrum knows

1) The possible location of licensed receivers
2) The frequencies they are using and their receive power levels at those frequencies
3) The performance of the licensed receivers
4) The emission mask of the TVWS device transmitter

then the database can determine the maximum transmit power that the TVWS device can use before it causes interference

Parameters (1) and (2) are typically estimated based upon propagation models used by broadcasters. The algorithms and accuracy of such models varies from country to country. For example, in Europe broadcast prediction models have been refined and verified over many decades and are now widely perceived to be accurate to within a few dB in most cases. Where there is doubt over their accuracy, margins are often built in to provide additional protection.

Such an approach has been proposed by Ofcom in the UK [3]. It has been approximated by the FCC in the US [4] where the emission masks of the TVWS devices have been fixed, as has their maximum output powers. While simpler, the FCC approach lacks flexibility. For example, it does not allow for devices with poorer transmit masks that might be able to access less white space but be produced at lower cost. The analysis in this article is performed using the more generic "Ofcom" approach — the "FCC" approach then becomes a special case for a given mask and transmit power.

The number of channels returned by the database can be improved through:

- Reducing the TVWS device transmit power and so decreasing the range over which it can cause interference.
- Reducing the TVWS device out-of-band emissions, which reduces the signal levels falling in band to the TVs.

Note that reduction in the out-of-band emission levels is only beneficial up to the point where the in-band emission from the TVWS device becomes the dominant interference case. So for example, with the TV protection margin ratios assumed in the UK [5], once the TVWS device transmitter out-of-band emission levels in a channel 1 away from the carrier ("n+1") fall below 50dBc, then interference will be dominated by the in-band signal from the TVWS interferer, and further improvements in these out-of-band emissions will not deliver any further gains in white space availability. (The FCC rules are for adjacent channel emissions to be at least 55dB down relative to the carrier; the analysis above suggests this is slightly over-strict and might be relaxed to 50dB.)

Interference from Licensed Users

The interference caused to TVWS devices from licensed use can be severe and is often a much more significant determinant of white space availability than interference caused to licensed users. There are three key sources of interference to a TVWS device:

- Signals from distant TV transmitters within its wanted white space channel.
- Strong signals on adjacent channels when close to TV transmitters that cannot be adequately filtered by the TVWS device receiver.
- Interference from other TVWS devices.

The last item cannot be predicted and will depend on the number of users and applications that eventually decide to use white space and is not discussed further here.

The first two can readily be predicted and measured. For example, signal levels measured near Cambridge, UK are shown below. This shows almost every channel, if measured with aligned polarization to the TV transmission, has signals above the noise floor, in many cases 10dB or more. If cross-polarization can be used, this can take some of the signal levels toward the noise floor, but this cannot be assumed in a system where terminals are mobile. Modeling across the UK suggests that in an average location with the best four to eight channels selected, the interference might be some 10dB above the noise floor — a very significant loss of link budget (Fig. 1).

As well as on-channel interference, white space devices may have to deal with very powerful signals on adjacent channels. For example, operation in almost any channel between 20 and 30 near Cambridge would result in receiving a signal at up to a power level of –40dBm on an adjacent channel. For a TVWS device needing to receive its wanted signals near the noise floor of –106dBm, this requires over 70dB of adjacent channel rejection in its receiver, if the link budget is not to be affected. By way of comparison, TV receivers have around 50dB of adjacent channel rejection.

Resulting white space availability will differ depending on the unlicensed device's capability in rejecting signals in adjacent channels. As this improves it becomes possible to operate closer to strong TV transmissions.

In some cases it can also be possible to reduce the effects of in-band interference. For example, simply by using cross-polar operation, some 5–10dB rejection of the TV transmission can be achieved and greater reductions are possible with more complex approaches. Systems able to reduce the impact of TV interference will have much greater white space availability than those that do not.

Simply by using cross-polar operation, some 5–10dB rejection of the TV transmission can be achieved and greater reductions are possible with more complex approaches. Systems able to reduce the impact of TV interference will have much greater white space availability than those that do not.

Results

Modeling all these different factors and determining white space availability is a complex process. We have built a modeling tool for the UK that is able to deliver detailed results. Our model

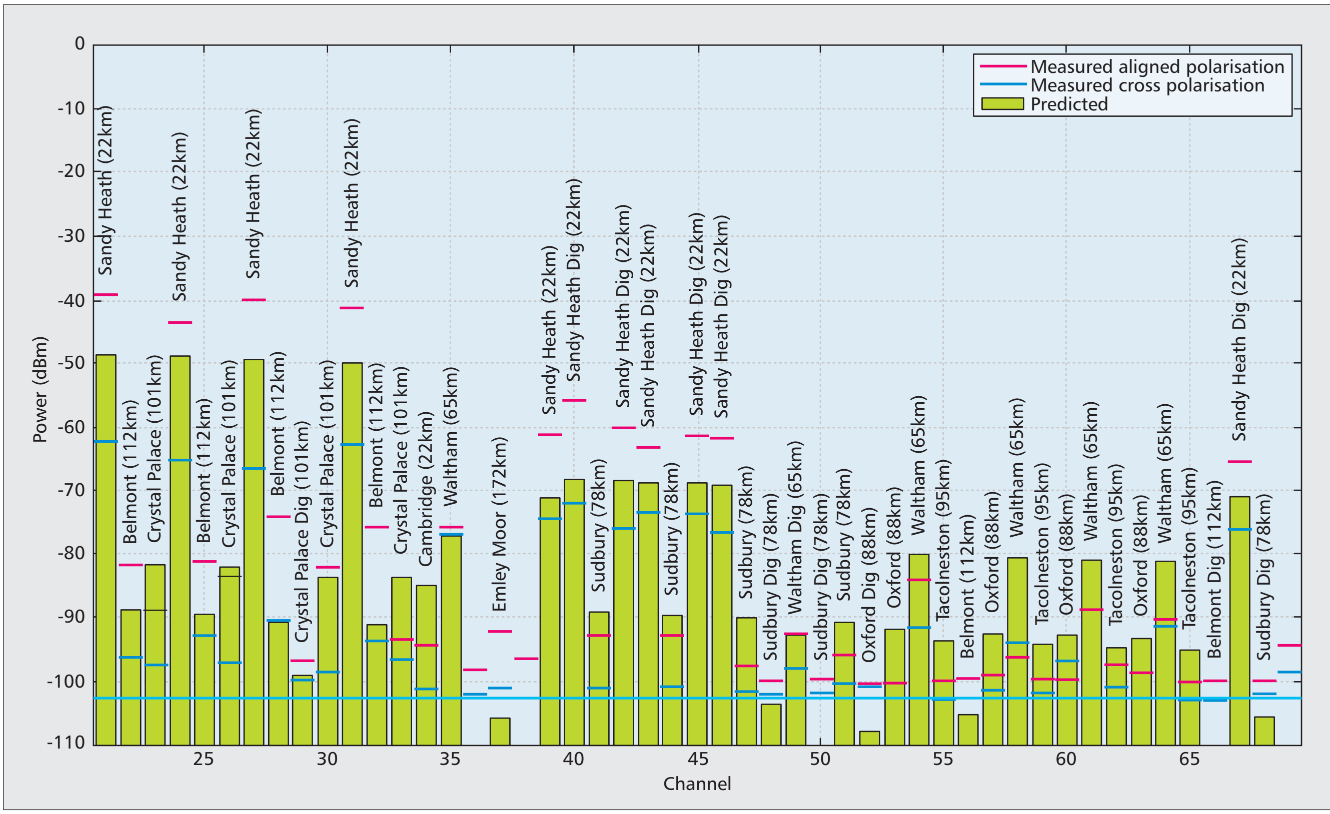

Figure 1. *Measured TV signal levels across the UHF band [Source: Neul].*

starts with a map of the UK coverage based on the UK TV transmitter locations, and uses a modified Hata model to predict the signal strength from each transmitter taking into account over-the-horizon propagation phenomena. It then models white space availability for a given TVWS device transmit power and TVWS device out-of-band emissions (OOB) characteristics. Finally, it rejects any channels where the technology will be unable to operate, either due to high co-channel interference from distant TV transmitters or strong signals on the neighboring channel that the technology is unable to adequately reject.

Results are provided for an optimized white space technology and a current technology (loosely based on WiMax and WiFi), taking into account all the factors discussed above. The assumed device parameters for the two technologies are are presented in Table 1.

Beyond a three channel offset, rejection is assumed to be perfect (i.e., any signal is completely filtered) and OOB emissions are assumed to be negligible. The optimized technology (based on an emerging, open, M2M standard termed "Weightless") uses cross-polar operation and antenna nulling steered toward the TV transmitter to deliver around 15–20 dB stronger rejection of TV signals than current technologies. It also has markedly improved transmitter filtering in order to achieve significant improvements in OOB emissions. Of course, any set of numbers could be modeled, but these have been selected as relevant and providing a useful comparison.

Table 2 shows the 50 percent white space availability (i.e., 50 percent of locations will have this amount or more white space available) and the percentage of points where no white space is available. The implications of this are different for peer-to-peer and networked technologies because a networked technology that has a lower transmit power level from the terminal device than from the base station may be able to site a base station just outside the area of non-availability and provide coverage into this area effectively at lower power levels.

The table also details the channel availability that would have been indicated by the TVWS geo-location database for an enquiry by the optimized technology. The latter is better than the results for the individual technologies as it does not take into account blocking due to strong TV signals on neighboring channels.

The tables provide results at four transmit (EIRP) power levels. Some of the key points to note are:

- As expected, lower transmit powers result in greater availability. Broadly, availability falls away steadily with increasing transmit powers.
- The database returns some channels that the technologies are unable to use due to interference to the unlicensed device. For example, at 0dBW the database indicates 152 MHz availability at 50 percent of locations, but the current technology can only access 16 MHz. This is due to blocking and interference from TV transmissions rendering many of the "white" channels rather "grey."
- An optimized technology can access approx-

imately five to ten times the amount of spectrum of a non-optimized technology, suggesting that "re-banding" of existing technologies into white space would be sub-optimal.

• The optimized technology is close to the technology that would be provided using only a geo-location database that ignored the effect of licensed transmitter interference on TVWS devices. This is because non-availability is dominated by the need to protect weak TV signals, and so the interference levels to TVWS devices are generally insignificant. Hence, a technology with good OOB emissions characteristics can achieve availability close to that indicated by the database.

Channel offset	Optimized Technology		Current Technology	
	Rejection (dB)	OOB emissions (dBc)	Rejection (dB)	OOB emissions (dBc)
0	15	N/A	0	N/A
1	40	55	20	28
2	65	65	40	50
3	80	80	60	70

Table 1. *Parameters for the "optimized" and "current" technologies.*

Figure 2 helps to illustrate why there are some areas with no availability and how regulation might be changed to improve this. It shows the predicted TV levels for the 32 white space channels in the UK (numbered sequentially rather than by actual channel number) at the four corners of a 1 km box drawn around a location with no availability:

It is immediately clear that this is an area of poor TV coverage. TV receivers can work to receive signal levels at around –80 dBm, and many of the signals here are only just above this level. There are no strong interferers. Hence, a lack of white space availability here is mostly to do with interference to TV signals rather than from TV transmissions interfering with TVWS devices. To investigate the problems further, it is helpful to isolate the channels that need protection. Clearly the only ones that need protection are the ones in this location that viewers are tuned to. When there is a dominant TV transmitter, it is clear which these are. When there are multiple weak transmitters, viewers could be tuned to any of the transmitters. This can often be seen in some locations where the rooftop TV Yagi antennas in a locality point in a range of directions. There is no "correct" answer to which transmitters to protect; instead, this is a regulatory decision balancing the protection to perhaps only one or two homes versus the loss of white space availability. A tractable way to analyze this problem is to use a "digital preferred service area" (DPSA) margin. This allows for reception of channels up to a certain margin below the signal strength of the strongest predicted transmitter in the area. Channels falling below this margin are assumed not to need protection.

In Fig. 2 the top right location has TV channels all at very similar signal levels right across the white space band. Here, TV signals from a number of transmitters are all equally good. Because these are at weak levels and TV receivers do not reject adjacent channels well, then typically the channel and the N+/-1 and n+/-2 channels become unusable for white space operation. The spacing of these channels is such that this effectively prevents any white space operation.

If the channel usage was as in any of the other "corners" then there would be substantial white space availability. A regulatory decision that only protected the transmitter providing these channels (each transmitter tends to transmit around seven channels) would result in around 12 channels (96MHz) of white space being available.

There are some very important regulatory decisions to be made regarding the DPSA margin that could dramatically improve the percentage of locations with no availability. Table 3 shows how key whitespace parameters change as the DPSA margin is varied for an optimized technology with 5 dBW output power.

As the margin increases, there is a steady degradation in channel availability and a very sharp degradation in the percentage of locations with no channels. So, for example, increasing the DPSA margin from 4 dB to 6 dB might prevent the need for a few thousand TV viewers to re-align their antennas but would prevent around 2.9 percent (7.3–4.4 percent) of the population from using white space. In the UK this would correspond to about 1.7 million people. If the cost of antenna re-alignment was judged to be

	Optimized		Current		Database	
EIRP	50% channels (MHz)	% no channels	50% channels (MHz)	% no channels	50% channels (MHz)	% no channels
–5dBW	120	1.1%	24	25.1%	184	1.0%
0dBW	112	2.0%	16	29.2%	152	1.9%
5dBW	96	3.2%	16	33.8%	136	3.1%
10dBW	88	4.7%	8	43.0%	120	4.5%

Table 2. *Comparison of different technologies.*

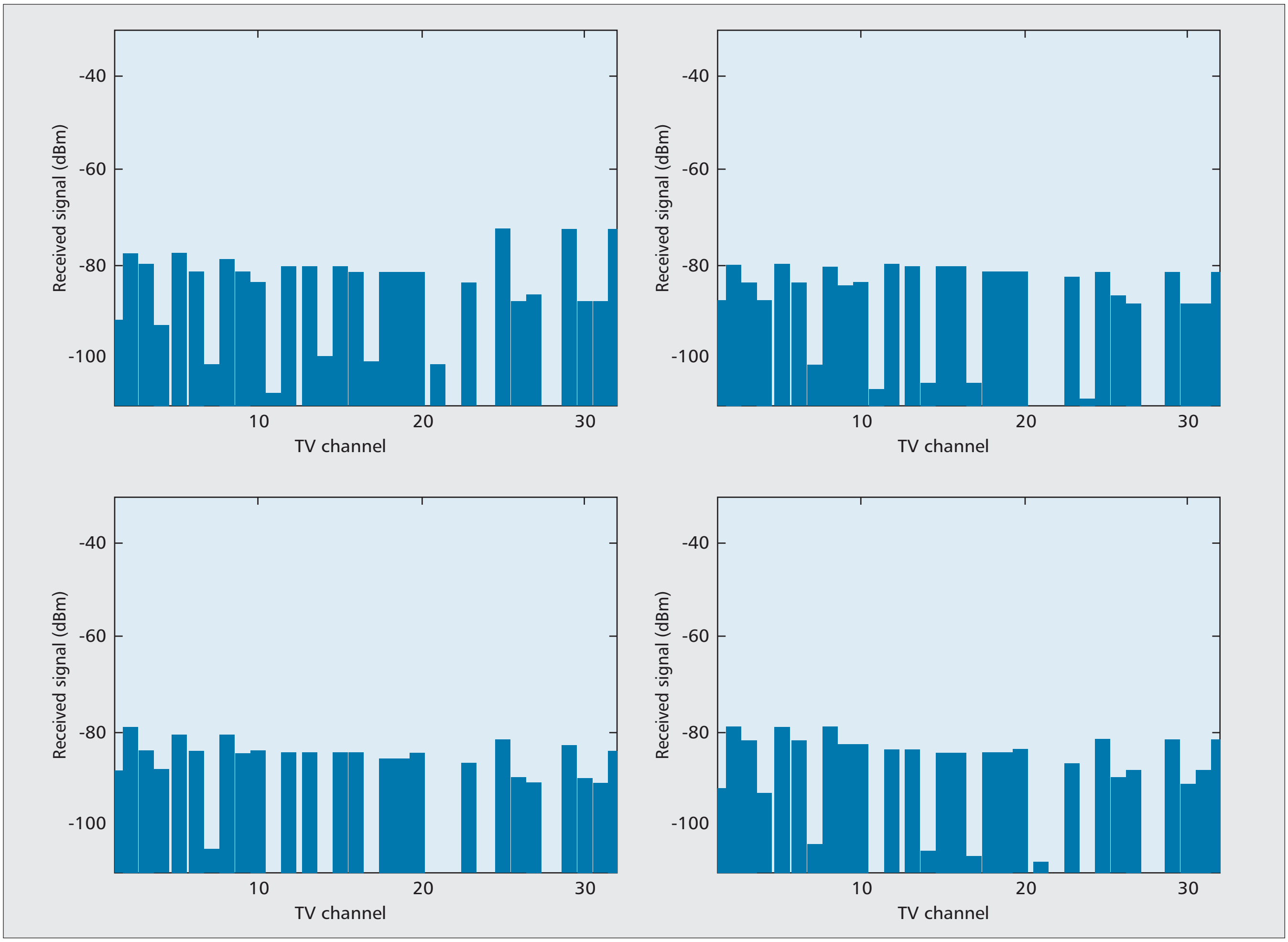

Figure 2. *TV channel predictions around an area of no availability.*

more than compensated by the economic impact of enabling more TVWS coverage, then a regulator should opt for a lower DPSA margin. However, with uncertainty around both the number of homes with badly oriented antenna and the benefits that will flow from white space, this is a decision that must be taken without full numerical analysis. Such a decision can, however, be modified if experience suggests it was inappropriate, with the white space database being updated according to any new DPSA margin. As a result, our recommendation would be to start with a low margin (e.g., 2dB) and monitor the subsequent use and interference.

Some regulatory environments are less flexible than the one analyzed here. For example, in the US, operation is not allowed on a TV channel that is in use, and fixed devices are also not allowed to operate on the immediately adjacent channels. If those rules were applied to the environment modeled in this article in the UK, the results would be as follows:

The impact of the different rules is profound. Under the FCC rules the number of locations with no availability triples compared to the Ofcom rules. It is clearly advantageous, then, for regulators to use the more complex algorithm set out earlier, rather than the simpler approach of preventing use on adjacent channels for higher power operation.

To summarize this section:

- White space availability is complex and can be dominated more by the interference to the TVWS user rather than to the licensed usage.
- Existing technologies are poorly suited to white space. Significantly better results can be achieved with an "optimized" technology rather than re banding an existing one.
- There are important regulatory decisions to be made regarding which TV signals to protect.
- A regulatory regime that allows for different transmit powers will hugely enhance the usefulness of white space.

We now consider the implications of these results to the applications and usage of TV white space.

Applications for Whitespace

The previous section set out a number of constraints associated with white space spectrum. These will have a major influence on the applications that are attractive to deploy in this spectrum. Regulators have concluded that avoidance of interference from white space devices is best achieved through a geo-location database access. This requires the device at one end of the link to determine its location and access the white space database without using white space in order to determine free channels. Depending on the application, this could be a significant burden for devices. For example, for a device-to-device application, say a camera sending pictures to a projector, one of these devices will need positioning technology such as GPS and an alternative communications mechanism such as cellular. This could add significant cost and complexity to the device. In some cases, such as when operating indoors, the positioning system may not work or there may be a lack of cellular coverage. Hence, for certain types of applications, the rules of accessing the spectrum might have a significant impact on its attractiveness. If the Ofcom rules are adopted, then devices may be assigned varying transmission powers depending on the white space availability in their location, which may result in some applications having significantly varying range or data rate depending on location.

Contrary to initial thinking [6], we conclude that the most likely applications in white space are "network-based" with devices under the control of base stations which then provide the connection back to the database [7]. This might be broadband, especially in rural areas, or machine-to-machine (M2M) across large geographies. The reason for this change in thinking is due to the change in regulation for white space access, from the sensing approach originally presumed to a geo-location approach requiring location awareness and database look-up. Also, a network-based solution can be designed with cell sizes appropriate to the power levels allowed for white space usage in the area, with smaller cells being deployed where lower power levels are available, such that a consistent quality of service is maintained.

The element of central control that comes with network deployment makes the regulations simpler but does mean that elements of the regulation designed to support device-to-device type applications may benefit from some additions or modifications. Existing white space regulation was developed assuming device-to-device communications such that the spectrum availability could be determined in a small area, although it is possible to consider larger coverage areas by making use of the "location uncertainty" parameter passed to the database. For a network such as rural broadband or wireless M2M, the database should check spectrum availability over the coverage area of each cell in the network. This can be approximated by assuming circular cells, but this will be inaccurate in some cases, particularly where the terrain is varying.

A better approach for networked systems is for the database to pre-store the known coverage area of each cell. It can then search across the area of the cell to determine which channels are available throughout the cell. This does not necessarily require any changed regulation as the database will be making a sequence of "point" enquiries, each of which are the same as would be performed for a device-to-device application in that area. However, it may be advantageous for the regulator to recognize "area enquiries" to the database such that they can verify that the database is working correctly at this level.

DPSA Margin (dB)	MHz Available	% with no channels
0	120	0.3%
2	104	1.9%
4	96	4.4%
6	88	7.3%
8	80	10.3%
10	72	13.7%

Table 3. *Variation in white space availability with DPSA margin.*

All at 5dBW[1]	Optimized		Current	Database (normal OOB, perfect rejection)
FCC rules	50% spectrum (MHz)	80	16	96
	No spectrum	9.7%	35.2%	9.3%
Ofcom rules	50% spectrum (MHz)	96	16	136
	No spectrum	3.2%	33.8%	3.1%

[1] Power levels for both FCC and Ofcom rules were fixed at 5dBW (i.e. the ability to reduce power levels to increase availability under the Ofcom rules was not enabled for this simulation).

Table 4. *Comparison of the "Ofcom" and "FCC" rules.*

Conclusions

In this article we have explored the availability of white space spectrum in some detail starting from the premise that there must be no increase in the interference that licensed users experience. The analysis takes into account not only the mechanisms needed to avoid interfering with licensed users but also the impact of the licensed transmission on the TVWS use, and we have shown that in some instances the interference to the TVWS use can be the dominant constraint. Consequently, for current technologies there can often be very limited white space availability, with a large percentage of locations where none is available. Optimized technologies with improved out-of-band emissions and the ability to reject TV interference perform much better, and we conclude that only optimized technologies can be viably deployed in white space spectrum.

Regulatory rules have a major impact on availability. In particular, simple rules, such as preventing adjacent channel operation, hugely reduce white space availability while not bringing any gains in terms of interference protection. Regulators should seek rules that are based on calculations of interference caused on a location-by-location and frequency-by-frequency basis.

Based on the need for optimized technologies, device location, database access, and the complexities of using white space, we conclude that, contrary to initial thinking, white space is better suited to deploying networks rather than for peer-to-peer communications.

These should include variable power levels, allowing white space devices to operate at lower powers in areas of poor availability, and taking into account the device emission characteristics. Those put forward by Ofcom in the UK appear generally appropriate. Regulators also need to give careful consideration to the extent to which TV reception is protected from multiple transmitter sites in areas of overlapping TV coverage, and ideally to quantify the number of viewers that might require antenna re-alignment against the reduction in white space availability.

Based on the need for optimized technologies, device location, database access, and the complexities of using white space, we conclude that, contrary to initial thinking, white space is better suited to deploying networks rather than for peer-to-peer communications. Promising candidates might be machine-to-machine wireless communications and rural broadband, which could effectively use the spectrum and deliver significant value to a country that enables appropriate regulation.

References

[1] D. Gurney *et al.*, "Geo-Location Database Techniques for Incumbent Protection in the TV White Space," *DYSPAN 2008 — 3rd IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks*, vol. 3, no. 1, Oct. 2008, pp. 232–40.

[2] M. Nekovee, "Cognitive Radio Access to TV White Spaces: Spectrum Opportunities, Commercial Applications and Remaining Technology Challenges," *DYSPAN 2010 — 4th IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks*, vol. 4, no. 4, Apr. 2010.

[3] See the Ofcom consultation published at http://stakeholders.ofcom.org.uk/consultations/geolocation/

[4] See the US Notice of Proposed Rulemaking published at http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-301650A1.doc.

[5] The "Blue Book" available from http://www.dvb.org/technology/standards/.

[6] J. Wang, M. Ghosh, and K. Challapali, "Emerging Cognitive Radio Applications: A Survey," *IEEE Commun. Mag.*, vol. 49, no. 3, Mar. 2011.

[7] M. Fitch *et al.*, "Wireless Service Provision in TV White Space with Cognitive Radio Technology: A Telecom Operator's Perspective and Experience," *IEEE Commun. Mag.*, vol. 49, no. 3, Mar. 2011.

Biography

WILLIAM WEBB (william.webb@neul.com) is one of the founding directors of Neul, a company developing machine-to-machine technologies and networks, which was formed at the start of 2011. Prior to this he was a Director at Ofcom where he managed a team providing technical advice and performing research across all areas of Ofcom's regulatory remit. He also spent three years providing strategic management across Motorola's entire communications portfolio, based in Chicago, he has published eleven books, eighty papers, and eighteen patents. He is a Visiting Professor at Surrey University and DeMontfort University, a member of Ofcom's Spectrum Advisory Board (OSAB) and a Fellow of the Royal Academy of Engineering, the IEEE and the IET where he is as a Vice President.