DSA Operational Parameters with Wireless Microphones

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***Abstract*—This paper provides a comprehensive analysis of Dynamic Spectrum Access (DSA) operational parameters in a typical "Hidden Node" scenario with wireless microphones in the TV white space situation. We consider all relevant effects and use an analysis framework that properly combines probabilistic technical factors to provide specific policy recommendations including the exclusion zone distances and the sensing-based DSA threshold detection levels.**

First, man-made noise measurements were taken in different locations and the amount of interference from man-made noise in potential wireless microphone channels was analyzed. Data collection results show that man-made noise levels can be up to 30 dB above the thermal noise floor.

Furthermore, indoor-to-outdoor path loss measurements were conducted to determine the required exclusion distance for DSA devices to ensure reliable wireless microphone operation in a typical application (a church). The results show that the required DSA radio exclusion zone can be safely and conservatively set at around 130 m when the results from man-made noise measurements and wireless microphone propagation measurements are used.

Additionally, we developed a simulation to determine the required DSA sensing threshold levels for impairment-free wireless microphone operation. An indoor-to-outdoor path loss model was created based on the above path loss measurement results. This statistical path loss model was used to determine the received signal level at DSA devices and at the interference level at wireless microphone receiver. Our results show that the sensing threshold can be set at around -110 dBm (in a 110 kHz channel) for impairment free wireless microphone operation when man-made noise and representative propagation models are used.

***Index Terms*— Dynamic spectrum access, exclusion distance, man-made noise, sensing threshold, wireless microphone**

I. Introduction

The opening of white spaces to new applications promises a range of economic and social benefits, by enabling the use of spectrum which has lain either unused or underused.

A. *Regulatory Progress*

Across the world, regulators are becoming aware of the importance of opening up white spaces for license-exempt use. Regulators in the US and the UK have sought to enable these gains without impacting the operations of existing users: mainly television broadcasters and wireless microphone users. In the US, proceedings on white spaces are now well advanced, building on the FCC's favorable decision [1] at the end of last year. In the UK, Ofcom published proposals [2] earlier this year for opening up white spaces to new applications.

One of the areas which regulators find particularly challenging is the determination of how to protect wireless microphones, which are well established in white spaces and are integral to the broadcast and movie industries. Data concerning real world wireless microphone system performance is sparse and operating practice not well documented. Difficulty in obtaining data on wireless microphone use and inaccurate methods to combine statistical factors has led regulators towards an unnecessarily conservative approach.

B. *Most Important DSA Issue*

The most important current DSA issue is to help regulators develop spectrum access policies that provide a fair balance between interference to legacy spectrum users and that are practical to implement. The difficulties encountered in the recent FCC white space testing and in the rule making process has not led to practical DSA rules. This is especially true for sense-based DSA rules which are currently unnecessarily conservative (Ofcom's -126 dBm sensing threshold) or non-existent (FCC). The lack of reasonable spectrum access policies is likely to impede the application of DSA unnecessarily.

There are DSA interference analyses in the literature. In [3], Dhillon et al performed an interference analysis at a wireless microphone receiver with single and multiple interferers. They concluded that DSA devices have the potential to cause some level of interference to wireless microphones; collaborative sensing will reduce the risk significantly. However, this paper doesn't consider many of the technical issues such as statistical multi-path propagation, probabilistic antenna front-to-back ratios, etc. that regulators are concerned with. Additionally, it doesn't provide specific DSA-sense based rule parameters such as required sensing threshold values. In [4], Gurney et al argue that geo-location method (dynamically updated databases) is better than spectrum sensing. Motorola also supports the use of geo-location databases by DSA devices [5]. Nevertheless, geo-location methods have multiple drawbacks such as: (a) The worst case propagation and wireless microphone temporal use assumptions that lead to low spectrum use, and (b) The cost and limitations of maintaining and being connected to TV station location databases. In [6], Buchwald et al and in [7], Yu-chun et al propose a disabling beacon system design which will protect the wireless microphones from DSA operation. 'Beacon' approach provides assured protection from DSA devices, but implementation is expensive since the system operator needs to purchase and deploy a beacon [8]. As a result, compared to geo-location and beacon signal methods, sensing based method is the most suitable method to protect wireless microphones.

C. Contribution of This Paper

In early 2009, we conducted a program of measurements and analysis to fill the information gap in wireless microphone operation. A key example is man-made noise, which has a significant if not dominant effect on the operation of wireless microphones in the field. By neglecting the impact of man-made noise in the calculation of wireless microphone protection requirements, regulators have arrived at technical criteria which overprotect microphones and unnecessarily impede new applications of white spaces. The results, presented in this paper, show scope for relaxing key technical constraints on the new white space devices.

In order to help regulators make more informed decisions in protecting wireless microphones from interference, the results of our analysis provides specific technical performance parameter recommendations. The results were used to estimate:

1) Geographic-based DSA rule: The minimum separation needed to avoid interference between a wireless microphone system and a white space DSA device operating in the same UHF channel. This separation defines the 'exclusion zone'.
2) Sense-based DSA rule: The minimum level to which white space DSA devices would have to sense, to ensure that they avoid using an occupied channel. This is related to the exclusion zone since, by definition, there is no interference risk from white space devices which are outside the zone.

The rest of this paper is structured as follows:

- Section II: The impact of man-made noise on wireless microphone operation
- Section III: A description of the geographic exclusion DSA method and the determination of reasonable exclusion distances
- Section IV: A description of the sense-based DSA method and the determination of reasonable detection threshold values
- Section V: Conclusions.

II. Impact of Man-Made Noise on Wireless Microphone Operation

DSA operation should impact the operation of wireless microphones an amount that is less than but comparable to the performance limitations due to noise. Man-made noise is often the dominant noise source, but is rarely considered in DSA analysis. This section develops wireless microphone performance estimates in the presence of man-made noise. As part of this study, noise and interference measurements were conducted in a range of locations, including private dwellings and public venues, in the state of Virginia, United States, in April 2009. The raw data for the measurements can be shared upon request.

A. A brief lexicon of noise

Noise forms a backdrop to wireless communications, determining the lowest signal level that can be received: i.e. the receiver sensitivity. There are two key sources of noise: thermal noise and receiver noise.

Thermal noise (also known as Johnson–Nyquist noise) is generated in electrical conductors at the radio frequency input of the receiver. These conductors include the antenna and any lead connecting it to the receiver. Thermal noise power can be calculated using the following formula[1]:

$$P_{dBm} = -174 + 10 \log10 (\Delta f) \quad (1)$$

where:

P_{dBm} is the thermal noise power, referred to 1 milliwatt

Δf is the bandwidth of the receiver input

The receiver also generates noise, further limiting its sensitivity. This latter component of noise, quantified in the receiver's *noise figure,* is a function of the nature and configuration of the components in its RF input stage. This paper brackets thermal noise and receiver noise together and refers to the combination as the *reception noise floor*.

In addition to noise arising in the receiver, there may be signals arising from external sources, which the receiver can detect. These may be either 'wanted' signals, from which the receiver can extract useful information or unwanted signals which impair the receiver's ability to recover the wanted signal. The unwanted signals are often referred to collectively as *interference* or *man-made noise*. In the case of wireless microphone operation in UHF, common examples of unwanted signals include signals from other wireless microphones operating in the vicinity and television transmissions.

White space devices are also a potential source of interference, if operating in the same channel and sufficiently close to the microphone receiver. The enabling regulatory framework for white space devices includes measures to protect wireless microphone operations, which need to be based on a solid understanding of the interference risk they pose.

In this paper, the risk of impairment to wireless microphone operation is gauged by determining the *Carrier to Interference and Noise Ratio* (CINR). CINR is the ratio between the wanted signal (referred to as the carrier) and an aggregated unwanted signal, in which man-made noise (aka interference), receiver noise and thermal noise are all included. Figure 1, below, illustrates how CINR relates to the received signal level, thermal noise floor and an *interference and noise* floor (in which man-made noise is also included).

The resulting value can be compared directly with the minimum value of CINR needed by a wireless microphone ($CINR_{min}$), to assure reliable operation. The minimum value of CINR is not published, but manufacturers indicate that 25 dB is a representative figure, appearing in the ERA report for Ofcom on cognitive access [9].

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[1] Based on an assumption of a 50 ohm source resistance at the receiver

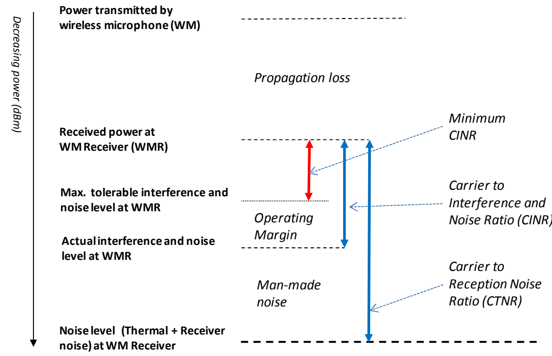

Figure 1. Carrier to Interference and Noise (CINR) takes into account man-made, thermal and receiver noise in assessing the margin available

B. *Establishing the level of man-made noise*

Regulatory analyses of wireless microphone protection requirements thus far have largely assumed that the noise floor at the wireless microphone receiver is equal to the reception noise floor – a parameter that is easily calculated from the bandwidth of the channel in question and the noise figure of the receiver. Little account has been taken of potential sources of interference other than white space devices. For example, although Ofcom's statement on cognitive access [2, Section 5.30 on page 21] notes that the typical set-up signal level at the wireless microphone is -67 dBm, it does not elaborate on the reasons for that.

Sources of man-made noise include television stations, electrical equipment in homes, offices, factories etc. Studio and stage environments have their own sources of noise, particularly other wireless microphones, as well as lighting system, lifting machinery etc.

The characteristics of man-made noise are well understood. Indeed, the ITU has long-established guidelines on typical levels of man-made noise that are to be expected in range of different locations [10], reproduced in Figure 2 below, which indicates the internationally accepted mean noise levels plotted against frequency, by location category.

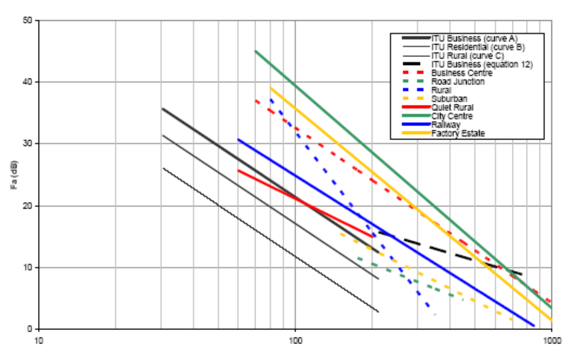

Figure 2. Man-made noise levels by frequency and types of location

F_a, represented by the y-axis, is the external noise figure of the system. It is defined as:

$$F_a = 10\log\left(p_n / kt_o b \right) \qquad (dB) \qquad (2)$$

where:

p_n : available noise power from an equivalent lossless antenna

k : Boltzmann's constant = 1.38 x 10^{-23} J/K

t_o : reference temperature (K) taken as 290 K

b : noise power bandwidth of the receiving system (Hz).

However, the ITU recommendation provides only *mean* levels, which are insufficient to determine the risk of interference to wireless microphones. It is the peak levels of such noise that cause problems, because the human ear is sensitive to even brief interruptions or artifacts in an audio signal. Therefore, we made noise measurements that took the noise's temporal variation into account.

C. *Man-Made Noise Measurements*

A spectrum analyzer and digitizer were used in conjunction with an omni-directional antenna to conduct measurements of noise (including the man-made element). The equipment configuration is shown in Figure 3.

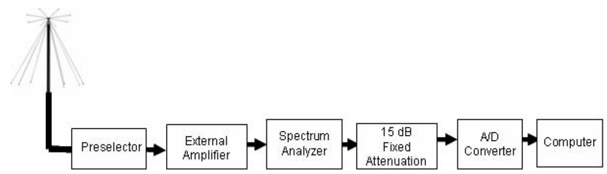

Figure 3. Man-made Noise Measurement Equipment

A wideband discone antenna (25-1300 MHz) was used in the man-made noise measurements. The SSC designed pre-selector module was used right after the antenna to reject outside band interferers. The gain of the pre-selector is 17 dB. An external amplifier with 3.7 dB noise figure and 23 dB gain was placed after the pre-selector to decrease the noise figure of the entire system. The signal was down-converted to 20.4 MHz in the spectrum analyzer and time series data was saved in the computer after A/D conversion. The sampling rate of the digitizer used was 12.8 MHz.

It is critical to select unoccupied test frequencies to make the man-made noise measurements. We used TV channels 16, 19, 21, 28, 37, 53, 56, 64, 65, and 69, which are unoccupied in the Tysons Corner, VA area. This was verified using rooftop antenna measurements on top of our 10 story high office building. All of the man-made noise measurements were made at ground level within a few miles of our office location. It is possible that wireless microphones were sometimes used in our experimental area. We made measurements of wireless microphone signals using the same equipment, and then we visually compared our noise measurements to ensure that no wireless microphone signals were present.

Measurements were made in 150 potential wireless microphone channels (200 kHz bandwidth), distributed over the ten vacant UHF TV channels, at a number of measurement points in each location. We made up to ten measurements on each of the 150 potential wireless microphone channels, over a period of up to 20 minutes.

High speed sampling was used to record noise in a central 3 MHz band in each of ten vacant UHF channels. Post processing was then used to subdivide each 3 MHz segment into 15 potential microphone channels (200 kHz in width) and to measure the noise level in each, as shown in Figure 4. Thus, distributed over ten UHF channels, there were 150 potential microphone channels examined at each location.

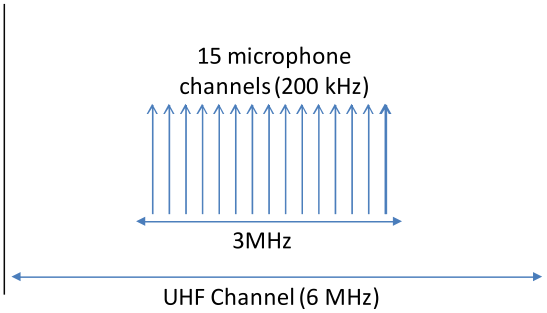

Figure 4. Measurements made in vacant UHF channels were post-processed into 150 microphone channels (200 kHz wide)

At each measurement position, each channel was sampled for 163 ms on 10 separate occasions to examine temporal changes in the noise level. This timing is illustrated in Figure 5. The measurement process was repeated at each of four to five positions at the four chosen locations.

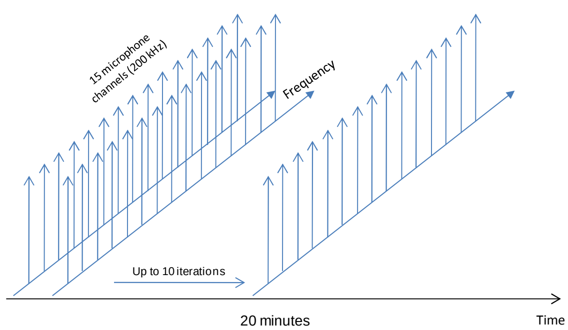

Figure 5. The time structure of the noise measurement sampling

An example man-made noise measurement is shown in Figure 6. Man-made signals are not Gaussian-type noise and contain large temporal and spectral features that are not Gaussian noise in character.

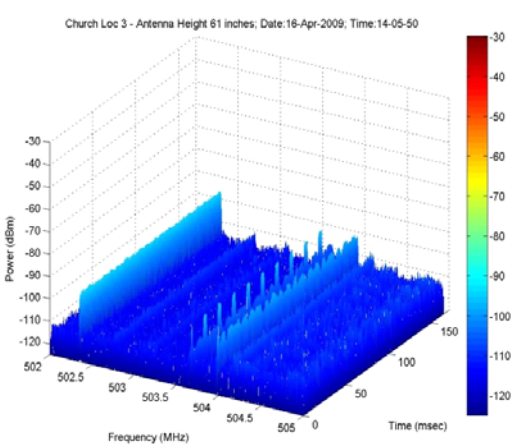

Figure 6. Typical man-made noise contains discrete spectral and temporal features that is significantly different than Gaussian noise

Man-made noise features are significantly above the thermal noise level. Figure 7 shows the man-made noise signal with a small bin FFT (48 Hz). The noise levels are >20 dB above thermal noise at some frequencies when 200 kHz FFT bin size is used.

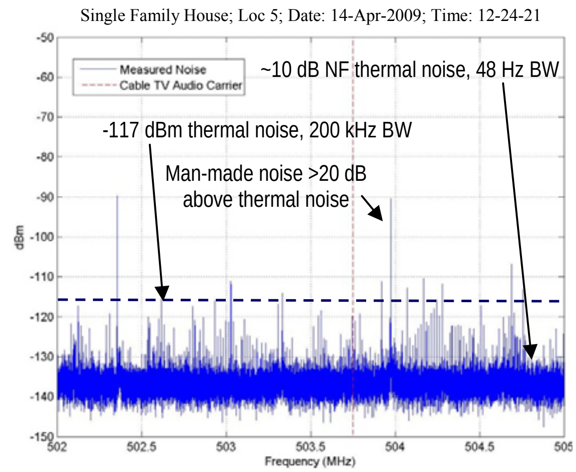

Figure 7. Man-made noise frequency plot using small FFT bin size (48 Hz) shows its non-Gaussian character and large amplitude

1) Calibrating the noise measurements

A noise source with 47 dB noise figure was used to calibrate the data collected. The noise module was connected to the collection equipment instead of the antenna and calibration data was collected with the same equipment settings as the actual data collection. A CW tone with a known signal power and frequency was injected to the equipment later on and test data was collected. Previously recorded calibration data was used to plot the CW tone signal to ensure that the calibration was done properly.

The first step in the measurement process was to determine the reception noise floor of the measurement system considering conducted and non-conducted emissions. To confirm the theoretical noise calculation, noise measurements were first performed at a relatively quiet location: the car park at Wolf Trap, Virginia, USA.

The reception noise floor of the measurement equipment (using a 200 kHz bandwidth) was confirmed as -110 dBm, given a theoretical thermal noise floor value of -121 dBm and equipment noise figure of 11 dB). Any signal value above this level was interpreted as man-made noise.

The Carrier to Reception Noise Ratio (CRNR) values given next in this paper are referred to a reception noise floor of:

1. -115 dBm, in the man-made noise impact sections, corresponding to a noise figure of 6 and a channel bandwidth of 200 kHz
2. -117.5 dBm, in the exclusion zone and sensing threshold section, corresponding to a noise figure of 6 dB and a channel bandwidth of 110 kHz. These bandwidth and noise figures were chosen to allow comparison with the results of ERA's analysis for Ofcom [9].

2) *Measurement Locations*

A total of 19 measurement points were used, distributed across four locations as follows:

1. Single family house and Flat 5
2. Flat (condo) 5
3. Church parking lot 4
4. Wolf Trap (an open air venue) 5

3) *Noise Power Distribution – from the measurements*

The following charts summarize the results of the measurements of the distribution of noise power in each of the four locations (single family home, condo, church parking lot, and Wolf Trap). The location is indicated at the top of each chart.

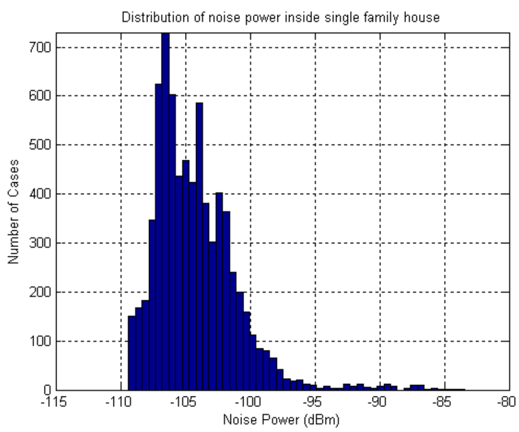

Figure 8. Noise levels distribution from measurements taken inside a single family house

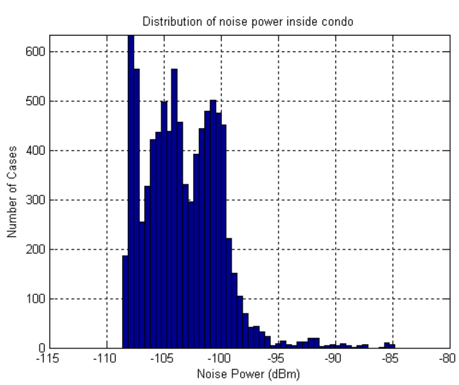

Figure 9. Noise levels distribution from measurements taken inside a condominium

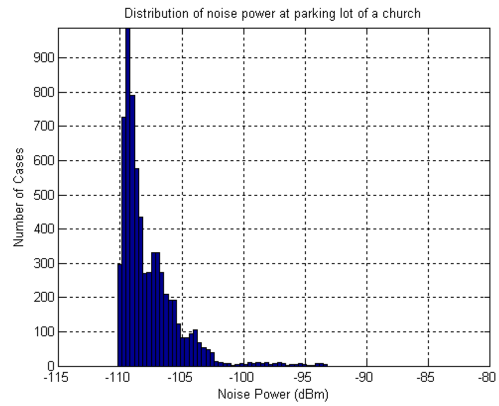

Figure 10. Noise levels distribution from measurements taken in a church car park

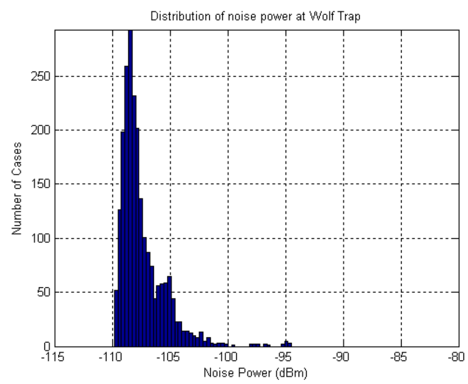

Figure 11. Noise levels distribution from measurements taken at Wolf Trap, VA

D. *Assessing the impact of man-made noise*

At each of the locations, SSC took a series of ten noise level samples, over a period of approximately 20 minutes, in each of 150 potential microphone channels distributed over 10 UHF channels. Thus a total of 1500 samples were taken in each measurement position. The process was repeated at between four and five measurement positions in each location, yielding a total approaching 30,000 noise measurements.

Figure 8 and Figure 9 show the distribution of noise levels found in a single family house and condominium, respectively. In these charts, it can be seen that man-made noise can range up to 30 dB above the thermal noise floor. [The thermal noise floor here is -115 dBm, using a bandwidth of 200 kHz and a measurement system noise figure of 6 dB.]

In order to assess the potential impact of man-made noise, we considered each of the 6000 to 7500 noise level samples taken, per location. For each of a range of wanted signal (carrier) levels at the wireless microphone receiver, and each measurement sample, we calculated the Carrier to Interference and Noise Ratio (CINR). If the result was greater than 25 dB, it was deemed that the noise level was *sub-critical* and thus microphone operation would not have been impaired in that particular channel at that time and place. The results of the calculation across the measurement sample base for each location are summarized in Table 1, below.

- The left hand column of the table indicates the signal level at the receiver in terms of its ratio to the thermal noise floor (i.e. the Carrier to Reception Noise Ratio (CRNR)). The adjacent column, on the right, shows the absolute signal power level received by the wireless microphone receiver[2].

- Each of the remaining cells in each row gives a score for each location, at the given CRNR value, corresponding to the ratio of *the number of samples in which the noise level was found to be sub-critical* to *the total number of noise level samples taken in that location*. For example, if, in 99 of 100 samples, the noise level was found to be sub-critical, then the *impairment-free* score would have been 99%.
- The right hand column of the table shows an impairment-free score calculated from samples aggregated across all the locations used.

It may be observed in Table 1 that a *Carrier to Reception Noise Ratio* (CRNR) of around 60 dB is needed to ensure impairment-free scores of 100% in all locations. Given that wireless microphones require a minimum *Carrier to Interference and Noise Ratio* (CINR) of 25 dB, this implies a man-made noise increment of around (60 dB - 25 dB =) 35 dB.

TABLE 1
THE POTENTIAL IMPACT OF MAN-MADE NOISE ON WIRELESS MICROPHONE OPERATION

Wireless Microphone CRNR (dB)	Received Power Level (dBm)	Proportion of samples where microphone operation would not have been impaired (%)				
		Location				
		Church Parking Lot	Inside Single Family House	Inside Condo	Wolf Trap Parking Lot[3]	All Locations
10	-104.9	0%	0%	0%	0%	0%
20	-94.9	0%	0%	0%	0%	0%
30	-84.9	0%	0%	0%	0%	0%
40	-74.9	98.3%	91.8%	84.2%	99.1%	91.5%
50	-64.9	100%	99.3%	99.5%	100%	99.6%
60	-54.9	100%	100%	100%	100%	100%
70	-44.9	100%	100%	100%	100%	100%

The results of the measurements and analysis, presented in Table 1, show that wireless microphone links typically need to be set up with a minimum Carrier to Reception Noise Ratio of approximately 60 dB, to be sufficiently protected from the impact of man-made noise, in all the venues measured.

It is worth remembering that the noise measurements described above were made in suburban areas. Undoubtedly the man-made noise levels in urban and metropolitan venues are even greater.

E. Users compensate for man-made noise by ensuring higher received signal levels

To compensate for the relatively high level of man-made noise experienced at most major venues, wireless microphone users need to ensure that received signal levels are much greater than would be needed if thermal noise were the only consideration. These augmented signal levels, achieved by minimizing the distance between microphone and receiver, allow wireless microphone systems to tolerate much higher DSA device signal levels than regulators have so far assumed.

III. GEOGRAPHIC EXCLUSION ZONE DSA METHOD

In order to estimate the required separation of a DSA device from a wireless microphone receiver using the same channel, it is necessary to be able to predict the propagation loss on a path between the two devices. However, there is no single propagation loss value corresponding to a particular distance, but rather a probability distribution of loss values. The measurement process, described below, enabled us to compile a database of propagation values over a range of distances, up to two kilometers from the test transmitter position. The raw data for the measurements can be shared upon request.

1) Propagation loss measurements

We carried out measurements of propagation loss for 4094 possible DSA device to wireless microphone receiver separation distances, ranging up to 2.7 km.

Extensive measurements were conducted at three public venues (churches), which were not in use at the time and whose wireless microphone systems had been switched off. Figure 12 shows the photos of inside Emmanuel Lutheran Church, one of three churches in which we located our transmitter.

Figure 12. Emmanuel Lutheran Church – the test transmitter was located inside

An indoor test transmitter with an emission power of 20 dBm (using a pure tone from a signal generator, centered on 556.36 MHz, with a stable frequency reference) was co-located with each venue's wireless microphone receiver, and coupled to an omni-directional antenna. The photo of the test transmitter is given in Figure 13.

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[2] This was obtained by adding the thermal noise floor level (a constant with value -115 dBm, calculated by adding the receiver noise figure of 6dB to (-174 dBm/Hz over 200 kHz,)) to the CRNR value in the first column.

[3] Wolf Trap is a public venue, which is known as a normally quiet location.

Figure 13. Inside church where the transmit equipment was located

A test receiver, mounted in a van, was used to measure the signal strength at a large number of locations around the outside of the venue. The receiver had an input bandwidth of 2.7 Hz, to facilitate a sensing limit of -158 dBm [calculated by adding the thermal noise level (-174+10log10 (2.7) = -169 dBm) to the receiver noise figure (11 dB)]. The propagation measurement equipment block diagram is shown in Figure 14.

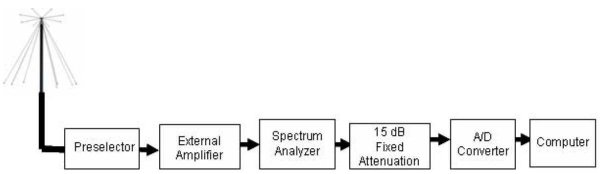

Figure 14. Propagation measurement equipment block diagram

The digitizer used for path loss data collection was different compared to the one used for man-made noise data collection. The sampling rate of the digitizer is 90 kHz for this set of measurements.

The outdoor receiver was linked to an omni-directional antenna, mounted on the roof of the van, with its height matched to that of the test transmitter (2 meters above the ground). This elevated location for the receiver antenna means that the measurement results understate the likely propagation loss suffered by a signal from a real DSA device: leading to a conservative exclusion zone estimate.

In total, measurements were made at 4094 discrete positions, achieved by driving the van around the outside of each church and tracking both the received signal level and the van position (using GPS). The measurements were captured and post-processed in MATLAB^{TM}. Figure 15 shows a typical result. This plot shows the van's route as it was driven around the church and the measured received signal level from the transmitter in the church.

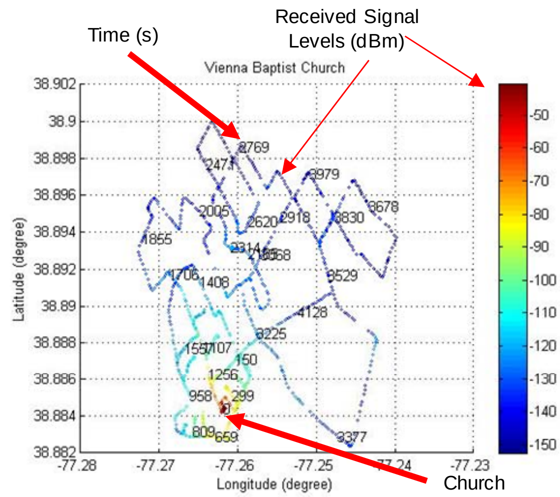

Figure 15 Example measured signal levels at different locations around a church used to determine the propagation loss.

The precise position of the receiver was recorded in the measurement process, but only the magnitude of its separation from the test transmitter, at each measurement point, was used in the subsequent analysis.

Since the measurements from each of the churches were similar, it was reasonable to combine them into a single data set consisting of a grid of 1 dB by 1 meter 'buckets'. A simplified representation of the data set is shown in the scatter plot (Figure 16) below. For each value of separation between the transmitter and receiver locations, the plot shows the distribution of corresponding measurements of the propagation loss. Lighter blue denotes a higher density of measurement points (2 to 3) than darker blue (1).

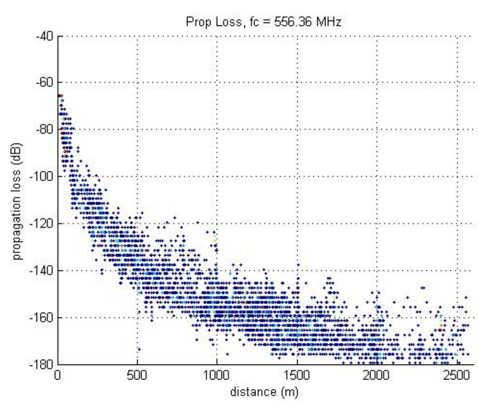

Figure 16. Propagation loss plotted against the distance between transmitter and receiver, for each of the 4094 receiver positions at which a signal level measurement was made

Red-M Services Ltd. also conducted similar path loss measurements in London in 2007 [11]. The transmitter was placed outside and path loss data was collected up to 2.5 km at 420 MHz. The test transmitter was placed inside in our measurements. As a result, expected path loss is higher compared to Red-M measurements. Figure 17 shows the results of Red-M data collection. SSC and Red-M results agree up to 500 m which is the distance of interest while setting the exclusion distance. The sensitivity of our equipment was higher, so we were able to measure path loss values up to -178 dB.

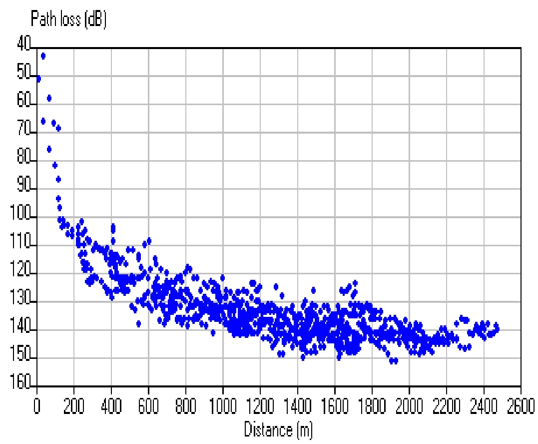

Figure 17. Red-M path loss measurements at 420 MHz in London

2) Estimating the required DSA exclusion zone size

Using the propagation loss measurements, acquired through the process described above, we were able to estimate the required separation of DSA device and wireless microphone receiver.

For each of a range of signal (carrier) levels at the wireless microphone receiver, it was possible to calculate the propagation loss required to prevent interference from a DSA device. The calculation assumed a DSA device transmission power density of 4.4dBm in a 110 kHz channel (equivalent to 20dBm in a 4 MHz channel). The DSA device was deemed not to cause interference, in a particular position, when the Carrier to Interference and Noise Ratio (CINR) remained above 25 dB at the wireless microphone receiver.

Figure 18 shows the same scatter plot as in Figure 16, overlaid with a red horizontal line showing the propagation loss required between the DSA device and the wireless microphone receiver to ensure a CINR (for the wanted signal) greater than 25 dB, when the wireless microphone signal level (CRNR) at the receiver is 60dB (i.e. a wanted signal carrier level of greater than -54.9 dBm, see Table 1). The matching vertical red line indicates the distance beyond which all data points had a propagation loss equal to or greater than the minimum needed, i.e. all data points fell below the horizontal line. This provides the most conservative (largest) estimate of the size required for the exclusion zone.

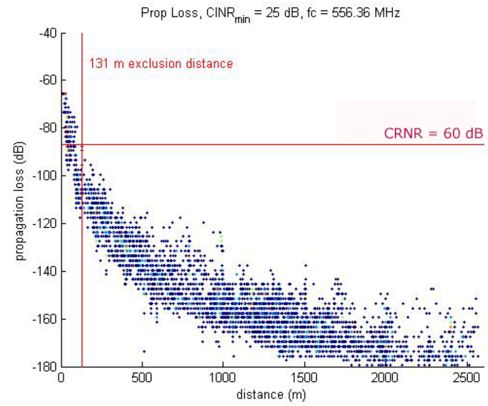

Figure 18. Required DSA device exclusion zone size for a given wireless microphone signal level

The reception noise floor used in this analysis is -117.5 dBm, calculated using a bandwidth of 110 kHz and assuming a receiver noise figure of 6 dB.

At the microphone signal level illustrated by the horizontal red line (-57.5 dBm, corresponding to CRNR = 60 dB), the required propagation loss to avoid impairing microphone operation can be seen from Figure 18 to be around -87 dB. This minimum value of propagation loss can be seen from the figure to have been achieved at all possible values of distance greater than that marked by the vertical red line: which can therefore safely be chosen as the boundary of the exclusion zone.

The results of estimating exclusion zone size, for a range of CRNR values, are summarized in Table 2. The proportion of measurements made at distances greater than or equal to the chosen exclusion zone size which meet the minimum propagation loss requirement, is referred to here as the *impairment-free score*. It corresponds to the percentage of positions outside the chosen exclusion zone, at which a DSA device would not have impaired microphone operation, when operating on the same channel. A score of 100% means that a DSA device operating on the same channel as the wireless microphone would not cause interference when located anywhere outside the exclusion zone.

The estimated exclusion zone sizes (radii) corresponding to each of a range of received microphone signal levels are presented in Table 2 below. The two right-hand columns of the table show how the exclusion zone could be contracted, if lower levels of impairment risk were tolerable.

TABLE 2
ESTIMATES OF REQUIRED EXCLUSION-ZONE SIZE FOR THE DATA SET IN FIG. 1 (DSA DEVICE TRANSMISSION POWER OF 20 DBM INTO 4 MHZ)

		Impairment-free microphone operation score		
		100%	**99.9%**	**99%**
Wireless Microphone CRNR (dB)	**Received Power Level (dBm)**	**Dynamic Spectrum Access Device Exclusion Distance (m)**		
30	-87.5	732	513	280
40	-77.5	304	246	132
50	-67.5	187	131	64
60	-57.5	131	82	<50
70	-47.5	81	52	51

Since man-made noise is significantly higher than thermal noise in areas where wireless microphones are used, such systems are evidently deployed with a much higher received signal than would be justified from assuming only that thermal noise applied. It is estimated that the received signal level used is typically in excess of 60 dB above the reception noise floor (i.e. Carrier to Reception Noise Ratio (CRNR) = 60 dB). Consulting Table 2, at this received signal level, a requirement for 100% impairment-free operation given these measurements leads to an exclusion zone, for DSA devices, of radius 131 meters.

In the typical downtown settings of major theatres and studios, public access is more restricted than at the venues where our measurements were made. Access to the stage and adjacent areas is often well separated from areas such as the foyer and auditorium where the public are likely to be found, isolated from main roads: for acoustic isolation as well as safety reasons. Assuming higher RF propagation loss too, our exclusion zone estimates are probably higher than are needed in practice.

[The reception noise floor used here is -117.5 dBm, calculated assuming a microphone receiver bandwidth of 110 kHz and a receiver noise figure of 6 dB, to be comparable with the values used in ERA's report on Cognitive Access for Ofcom [9]]

IV. Sense-Based DSA Method

The previous section established that taking man-made noise and realistic propagation losses into account provides significant scope for limiting the exclusion zone. Regulators currently seem to prefer DSA devices to find vacant UHF channels through geo-location, whereby the devices look up which channels are vacant at their position in a database.

However, some DSA devices may rely on spectrum sensing in order to check that a channel is free. For these devices, it is important that sensing thresholds are sufficiently low to protect microphones (and TV reception), but not so low as to make DSA devices unnecessarily costly, difficult to produce and liable to detect unoccupied channels as occupied. In this section, we consider how these factors impact the sensing threshold requirement.

In general, the sense-based DSA method is able to estimate the link loss between the DSA transmitter and the "victim" transceiver by measuring the received power level from the "victim transceiver" and knowing the victim's transmit power level. Estimating this link loss enables the DSA radio to adjust its transmit power level (or to decide to transmit or not) to avoid causing unwanted interference to the "victim" receiver.

In the wireless microphone situation, the "victim" wireless microphone receiver does not transmit a signal, hence, the receiver is a "hidden node". The DSA radio estimates the minimum "likely" link loss between the DSA radio and the wireless microphone receiver (L3) by measuring the wireless microphone to DSA radio link loss (L2). This is shown in Figure 19.

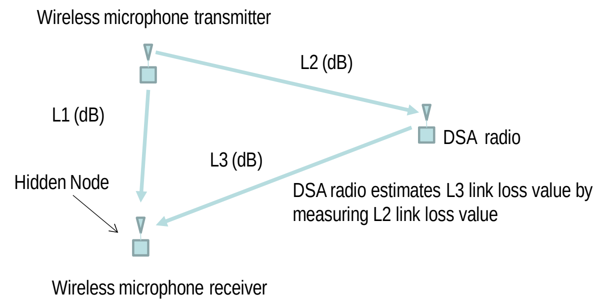

Figure 19. The wireless microphone receiver is hidden from the DSA radio

The DSA radio continually measures the received signal level from the wireless transmitter. If the received signal level is above the sensing threshold, the DSA radio doesn't transmit. Because of the hidden node problem, the risk of interference to the wireless microphone is a complex, statistical function of the sensing threshold value.

A. *Simulation Description*

To establish a relationship between impairment-free wireless microphone operation and the value chosen for the sensing threshold, around one million randomly-chosen possible combinations of wireless microphone, wireless microphone receiver and DSA device positions were considered, using the propagation loss data gathered as described above. For each position combination, a calculation was made of whether microphone operation might have been impaired or not.

In order to generate the large number of possible position combinations required, we used a Monte Carlo simulation. Fixing the wireless microphone receiver at the center, the simulation generated one million different combinations of wireless microphone (transmitter) and DSA device position, over area of 1 square kilometers. This is illustrated in Figure 20, following.

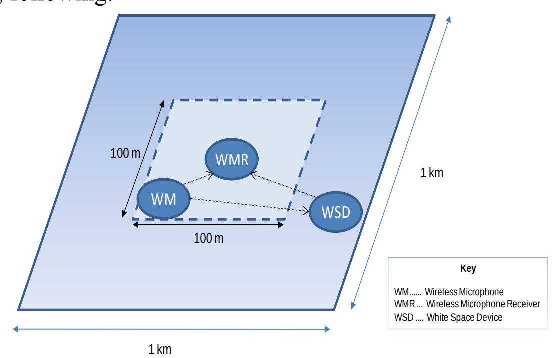

Figure 20. Simulation field for analysis of the sensing threshold requirements, for DSA devices

The basis for the simulation was as follows:

- The wireless microphone receiver (WMR) was positioned at the centre of the grid
- The wireless microphone (WM) was limited to positions within a 100 m square subset of the 1 km square grid
- The DSA device was allowed to range anywhere within the 1 km by 1 km grid

- For each point in the simulation, a propagation loss value was chosen at random from the values measured earlier, for the given distance between wireless microphone and DSA device
- In 5% of the points, the propagation loss was increased by 20 dB to account for body loss (amounting to 50,000 out of the 1 million simulated cases)
- The wireless microphone transmission power was taken as 14.8 dBm, with a system bandwidth of 110 kHz. [A noise figure of 6 dB was used for the wireless microphone receiver, yielding a reception noise floor of -117 dBm]
- The DSA device's transmission power was taken as 20 dBm within a transmission bandwidth of 4 MHz, amounting to 4.4 dBm in a 110 KHz channel.

Figure 21 shows the simulation area with wireless microphone transmitter, receiver and DSA devices.

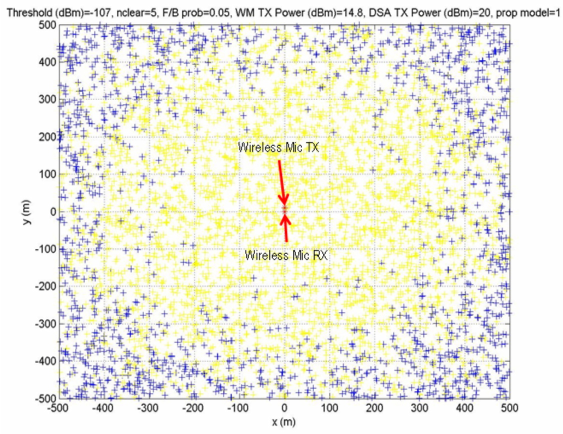

Figure 21. Wireless microphone simulation area

A -107 dBm threshold level was used as the sensing threshold in Figure 21. The DSA nodes with yellow color have turned off since the received power level from wireless microphone transmitter is above the -107 dBm sensing threshold. Blue DSA nodes are the ones which will cause interference to wireless microphone receiver. The amount of interference from DSA nodes to wireless microphone receiver in case of miss detection was analyzed in the simulation.

The propagation loss model used in the simulation drew directly on the measurements described in the previous section. It was applied to transmissions between wireless microphone and the DSA device as well as between the DSA device and wireless microphone receiver, using the assumption that the model was applicable to all paths ending within the central 100 square meter zone allowed for microphone roaming in the simulation.

No path loss assumptions were made to calculate the received signal level at wireless microphone receiver from wireless microphone transmitter. The CRNR values used in Table 1 and Table 2 (30 dB, 40 dB, etc) were used to calculate the received signal level at wireless microphone receiver in the absence of DSA devices.

For each synthesized position combination generated by the simulation, the distances between the DSA device and wireless microphone transmitter and DSA device and wireless microphone receiver were calculated and corresponding propagation loss values were retrieved from the propagation loss measurement base. Since the measurement base included a number of possible propagation loss values for each value of distance, the particular value retrieved by the simulation was chosen at random from the set of applicable values for the distance in question. For example, if a distance of 90 meters corresponded to propagation loss measurements of between -80 and -100 dB, the value used by the simulation would have been chosen at random from values measured within that range. In 5% of cases, 20 dB was added to the propagation loss to simulate the effect of body absorption [12].

The sensing threshold versus failure rate plots were created at the end of the simulation for each different CRNR level. A typical simulation result is shown in Figure 22. As seen in the figure, a threshold level of -111 dBm is enough to make sure that wireless microphones always operate reliably when CRNR is 60 dB or more.

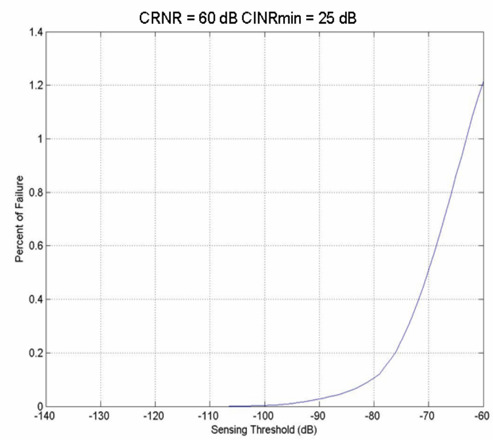

Figure 22 Typical simulation results provide the sensing threshold versus failure rate plots

B. *Estimating the DSA Sensing Threshold*

The results of the simulation are presented in Table 3 below, with estimated sensing thresholds corresponding to a range of possible wanted signal levels at the microphone receiver. In the third column, the sensing threshold value given ensures 100% impairment-free operation – meaning that in all the cases in the simulation, either the wireless microphone signal was detected by the DSA device, or the DSA device was sufficiently separated from the wireless microphone receiver for its transmissions not to impair microphone operation. For example, if the Carrier to Reception Noise Ratio (CRNR) equaled 60 dB, a sensing threshold requirement of -111 dBm, for the DSA device, would have been sufficient to protect wireless microphone operation from impairment, when both were using the same microphone channel. Either the DSA device would have been able to detect the wireless microphone, at the specified threshold, and it had moved to an alternative channel or its signal would have been sufficiently attenuated at the wireless microphone receiver.

The two right hand columns of Table 3 show how the required sensing threshold could be relaxed if a small impairment risk to microphone operation were tolerable.

TABLE 3
ESTIMATED SENSING THRESHOLD VALUES FOR DSA DEVICES (WITH DSA DEVICE TRANSMISSION POWER OF 20 DBM INTO A 4 MHZ CHANNEL)

		Impairment-free microphone operation score		
		100%	**99.9%**	**99%**
Wireless Microphone CRNR (dB)	**Received power level (dBm)**	**Dynamic Spectrum Access Device Detection Threshold (dBm)**		
30	-87.5	-144	-144	-141
40	-77.5	-133	-122	-98
50	-67.5	-119	-101	-84
60	-57.5	-111	-85	-69
70	-47.5	-104	-71	>-60

The reception noise floor used as the reference for CRNR here, is -117.5 dBm, calculated assuming a bandwidth of 110 kHz and an equipment noise figure of 6 dB, comparable with ERA's analysis for Ofcom [9].

V. CONCLUSIONS

The conclusions of this study are as follows.

A. *Man-Made Noise*

The effects of man-made noise have not properly been taken into account in protection analyses to date. Reception noise floor has been considered while determining the maximum allowable interference-to-noise ratio for DSA devices. On the other hand, many other devices impact wireless microphone operation more than DSA radios and this study shows that man-made noise is one of the dominant factors that interferes with wireless microphone operation.

ITU man-made noise measurements show that man-made noise levels are on average 14 dB higher than reception noise floor in city centre (at 500 MHz) and our measurements in suburban areas show that the peak man-made noise level can go up to 30 dB above the reception noise floor. As a result, wireless microphones have to have high CRNR values (>60 dB) in order to operate reliably. Since wireless microphones have high signal margins, interference from cognitive radios (i.e. DSA device) will be negligible. Man-made noise levels should be taken into consideration while determining the requirements for DSA operation. A reasonable requirement for DSA radios would be to impact the noise level by no more than 10 dB, for less than 3% of the time.

B. *DSA Exclusion Distance Method*

SSC conducted propagation loss measurements in suburban areas to determine the required exclusion distance for DSA devices. When man-made noise and representative propagation models are used the required exclusion zone can be safely and conservatively set at around 130 m.

C. *DSA Sensing Method*

DSA detection threshold depends on statistical parameters. DSA device can measure the path loss between DSA device wireless microphone transmitter, but it can not measure the path loss between itself and wireless microphone receiver. As a result, there is hidden node factor in wireless microphone sensing threshold calculations. Furthermore, there is multi-path, blockage, body loss factors which make the detection of wireless microphone signals more difficult. The total probability of probabilistic parameters should be considered together while calculating the required sensing threshold level instead of combining worst case of each of these individual factors. On the other hand, wireless microphone receivers always experience high interference levels because of man-made noise, co-channel wireless microphone signals and broadcast TV signals. Considering the fact that wireless microphones have to have high signal margins in order to operate properly, when man-made noise and representative propagation models are used the required sensing threshold can be set at around -110 dBm (in a 110 kHz channel).

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