Small Scale DAB

The potential for lower-cost transmitting stations in support of DAB rollout

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Section 1

Summary

1.1

An experimental DAB multiplex was set up in central Brighton between 14th September 2012 and 27th January 2013 using new lower-cost technologies. The experiment was privately-funded, and the research conducted in the author's spare time. As no similar study had previously been carried out, the test was a valuable exercise to inform policy makers of the practicalities of low cost DAB solutions when used to serve small areas, particularly from a single transmitter. The transmissions were operated under a Non-Operational Test and Development licence issued by Ofcom.

As well as testing the viability and reliability of new wireless techniques for generating a Eureka 147 DAB compliant signal in a real world scenario and it also allowed various measurements, and comparisons with existing multiplexes to be made. The experiment successfully demonstrated that much of the infrastructure can now easily be implemented in software, and that integration with public IP networks improves accessibility while reducing the capital and operating costs quite dramatically. It was also demonstrated that a trade-off in power amplifier selection could remove the need for large and costly cavity filters to meet ITU spectral masks. The trade-off is a reduction in power efficiency, but the cost of this is negligible at low power levels. Some thought was also applied as to how a small-scale multiplex could fit in with the current and future radio broadcasting spectrum landscapes. It was also shown that a low-cost, low power approach could deliver a reliable, high quality service at minimal opportunity cost by using interleaved spectrum, which is unsuitable for use by larger networks.

The experiment also highlighted the importance of 'site over might'. Low power transmitters sited in urban population centres can often deliver the field strengths required for reliable indoor reception much more effectively than might be achieved with a higher-powered site on the periphery of the population centre.

Adjacent Channel Interference (ACI) to other DAB services was anticipated and thoroughly checked for, but none was found. It seems that ACI 'holes' are not created by low power DAB transmitters sited in an area where the wanted signal levels from other multiplex services transmitted from elsewhere are sufficiently high.

This work demonstrated that it is feasible to deliver DAB transmission infrastructure at much lower cost than currently required for equipment to deliver wide-area coverage. Nevertheless, significant further work is required to identify suitable spectrum for services making use of these technologies. In addition, it will be necessary to consider how they might be licensed to cover particular areas, especially in circumstances where there is a requirement to carry more than one service on the multiplex. When these issues have been resolved, these new techniques could find particular application for Community Radio or smaller scale commercial radio stations. These techniques might also assist in rolling out existing networks to serve more remote population areas where existing approaches might not prove to be cost-effective.

This report is intentionally light on engineering details (although it does use many technical terms) as the goal is to provide an outline of new concepts that can be understood by an audience with varying depths of understanding in technical matters. Although a wide range of different products and tools is given, their inclusion as a reference in this document should not be taken as an endorsement of these products and tools.

Section 2

Introduction

2.1

The final patents associated with the Eureka 147 DAB standard expired in January 2013 (in most of the world) making it the first free ‘open’ digital radio broadcasting standard. DAB may be around twenty years old but its transmission system is based on the COFDM modulation scheme that forms the basis of most modern transmission systems. It also includes time-interleaving which gives DAB immunity to impulse noise. In addition, it has an inherent immunity to the effects of multipath fading due to its wide bandwidth, and a relatively low signal-to-noise requirement because of the robust modulation scheme. Other systems such as DRM+ (which is an open standard, albeit subject to patents) and the ‘HD Radio’ system are also available for local broadcasting in certain regions. Both of these are narrowband systems, and essentially, can only carry a single main programme due to the low capacity. This means that separate transmission infrastructure is needed for each service. There may also be a greater need for additional transmitters to compensate for fading in a high multipath reception environment.

Open standards are attractive to manufacturers seeking to enter new markets, particularly where there are no entry fees or patent pool royalty payments. Open source code is already becoming available that allows DAB receivers to be implemented wholly in software: proof-of-concept receivers have already been demonstrated running on ARM processor powered devices. These include a Raspberry Pi educational computer, and a Google Nexus tablet. Although these are currently a world apart from the low power module-based sets on the market today, it is anticipated that as gains in power efficiency are made (driven by the aggressive competition in the mobile ‘smart’ devices market) it will become easy to decode DAB and other standards entirely in software without excessive battery drain. It is easy to imagine that the inclusion of a versatile wide-band tuner with a baseband processor in smart devices would be a logical step for some smart device manufacturers hoping to gain market share. Implementing a concept receiver using a computer and a very low cost Software Defined Radio USB stick (marketed as a TV receiver) is already possible - these devices contain a tiny tuner chip which covers 60~1700 MHz, and can be used to directly sample quite large spectral bandwidths within this range for subsequent processing on the host device.

This interesting development is part of the current Software Defined Radio (SDR) revolution. SDR is a technological development which has implications for all spectrum users. As well as reception, SDR also opens up new possibilities for signal generation. It is an enabling technology which is encouraging more specialists to develop competitive products. The implication for DAB is that it is already possible for engineers to create their own modulators, complementing the already available ‘open source’ audio source encoders and ensemble multiplexers. A complete suite of software called ‘mmbtools’ has been released by two researchers at the Canadian Communications Research Centre, and is free to download.

A significant advantage of open source software is that anybody can access the original source code from which the software applications are built. This makes it possible to customise the applications to meet specific needs, or to build new maintenance releases. The Internet also enables users to help each other to produce bug fixes, implement enhancements or produce custom versions for different purposes. There are several different codebases in the public domain that can be used without modification to build the various elements of a DAB network.

Section 3

SDR Technology

3.1

Software Defined Radios are just beginning to proliferate - the number of sources of SDRs is increasing and their prices are falling steadily. The user base is also rapidly expanding. Not only do SDRs have the potential for DAB transmission (and reception), but also the flexibility ensures that SDRs will become widely adopted in wireless communications over the coming years.

The physical SDR unit is generally a computer peripheral that contains a fast analogue-to-digital converter for reception, and a digital-to-analogue converter for transmitting. There are also computer-controlled frequency synthesisers, mixers, arrays of programmable logic and I/Q modulators. These building blocks can be programmed through software to function dynamically. Because many wireless communication systems can be implemented entirely in software in this way, the concept will impact traditional system design and manufacturing of future wireless communication systems.

Secure wireless communication systems can also theoretically be reverse-engineered and simply emulated with an SDR. Previously the development resources required by individuals to replicate these complex communication systems would have presented an insurmountable barrier. The Internet also provides a workspace for those with a common interest in particular systems. The software implementations can simply be worked on by an online ‘crowd’ of developers who can instantly distribute the implementations by posting them for download. In addition to DAB transmitters, other systems can already be simulated by experimenters and security specialists using SDR technology. An example is an experimental GSM (2G) mobile phone base station which can be run (along with a software switch such as ‘Asterisk’) on a single PC and an external SDR transceiver - this would have been unimaginable just a few years ago. This particular project has been tested ‘in the wild’ through an FCC licensed test network deployed in the Black Rock desert of Nevada, USA, and also to provide an interim mobile phone service in the South Pacific by Telecom Niue.

It is possible that many wireless communication systems could become based largely on SDR technology in the future and software updates would enable them to be kept secure. The only option for a compromised system based on application specific technology would be the complete replacement of the system hardware.

Section 4

Open Source Software

4.1

The infrastructure in DAB networks has traditionally been of proprietary design. Low cost, generic PCs are sufficiently powerful today that all of the network elements can now be implemented as software applications. This circumvents the traditional hardware development cycle which involves complex, application-specific electronic circuitry which is both costly to design, manufacture (in the low volumes associated with broadcasting equipment) and difficult to maintain. As such, designs based on software applications remain free from issues such as component obsolescence. In addition to ready-made low-cost hardware, the free GNU Linux operating system provides a secure, stable and highly flexible toolbox. Linux is used as the code base in an ever growing number of commercially available communication devices and is now the operating system of choice in an array of consumer electronic devices including smart phones, Internet routers, and set-top boxes and it is also the operating system which underpins the public Internet. For DAB use, the various software network elements consist of a number of freely available, application layer programs running on Linux, instead of the usual commercially available dedicated infrastructure.

With open-source software, all of the code that the binary executable files are built from is freely available. This enables anyone to modify, maintain, or customise it - no part of the software design or operational process is hidden from the view of the end user. This freedom allows users of open source software to remain in complete control of the future of the technology that they have invested in, which is somewhat different to a manufacturer being in control of the product life cycle. A brief description of the main open source applications used to build a DAB transmission platform is included in the following sections.

4.2 Mp2 Audio Source Encoding

TooLAME is a free software MPEG-1 Layer II (MP2) audio encoder. While there are many MP2 encoders available, TooLAME is well-recognised for its particularly high audio quality. It is lightweight and extremely fast, which means many real-time instances can be run concurrently in a single CPU core. In addition to the psychoacoustic models contained in the ISO standard, TooLAME is able to encode using a number of other models including a highly tuned model developed for LAME (which is an ‘mp3’ compatible codec). It is also possible to adapt or create entirely new (but backwards compatible) psychoacoustic models. TooLAME supports Frame CRCs, and Broadcast Wave Format output which is used in DAB. Currently, the PAD and X-PAD DAB extensions used for the text displayed on radio sets are simply padded space with no data and therefore an external DLS inserter is currently required in order to send programme associated data when using this codec.

4.3 Ensemble Multiplexing

CRC-DABMUX is a DAB/DMB software multiplexer developed at Communications Research Centre (CRC) - the Canadian federal government's primary laboratory for research and development in advanced telecommunications. CRC employs around 400 staff and it operates with an annual budget of around C$50m.

Two researchers at CRC developed several tools to support activities in the area of mobile multimedia broadcasting (MMB). In September 2009, CRC-DABMUX was released as a free, open source software product under a GPL licence. The software produces ETI compliant bit streams that can be injected directly into DAB modulators or indirectly through another level of DAB multiplexing. Because of its software-based architecture, many typical DAB services can be generated and multiplexed on a single PC platform with live or pre-recorded sources. It is also a very useful tool for application and receiver functionality testing or as a portable demonstration platform. Most standard DAB transport mechanisms have been fully (or at least partially) implemented: FIDC, MPEG audio, enhanced packet mode (EPM), stream mode and DMB. The multiplexer was developed for the GNU/Linux operating system (OS) but can also be compiled to run on the Microsoft Windows platform.

CRC-DABMUX offers many input options for the insertion of encoded applications including: files, UDP/IP and TCP/IP ports. The signalling information is auto-generated and is sent over the fast information channel (FIC). The resulting ETI-formatted bit stream can be provided with many output options as well: e.g. TCP/IP, UDP/IP, files and G.703 physical interfaces. In 2012, a patch was released by Swiss engineer Matthias Brändli, which added Single Frequency Network support along with several other enhancements including time-stamping (MNSC/TIST) of DAB frames for Single Frequency Network purposes.

The multiplexer also supports the FarSync TE1 physical interface board produced by FarSite. With this interface, a G.703 NA compliant signal can be generated and inserted directly into existing commercial DAB/DMB modulators which may only have an interface for the ensemble input. The ETI bitstream can also be sent directly into another Open Source application called Openmokast (also written at CRC) which is useful for monitoring, development and testing.

For the experiment, an old dual core 2 GHz Pentium desktop PC was initially used and it performed perfectly well as a multiplexer. The multiplexer software also ran perfectly on a low cost Internet based VPS (in the cloud) and at the time of writing it continues to do so. After the experiment had ended, a quick investigation showed that it was easy to port the multiplexer software to ARM* architecture and run it on a £30 Raspberry Pi educational computer.

**Small ARM-based general purpose computers like these have no moving parts (e.g. hard disks) and utilise flash memory, making them an ideal platform for low cost, reliable source encoders and ensemble multiplexers.*

4.4 COFDM Modulation

CRC-DABMOD is a basic software implementation of a Eureka 147 DAB modulator for UNIX-like platforms. It supports all DAB transmission modes, and produces a modulated output in the form of complex sample with I/Q components. It can use platforms such as the USRP from Ettus Research that is a well known and widely supported Software Defined Radio system. The USRP provides digital-to-analogue conversion and RF components for the transmission and reception of signals in different spectrum bands. The modulating waveforms generated on the PC can be transferred via various interfaces to a digital-to-analogue subsystem. In 2012, a patch was released by Matthias Brändli which added support for the software modulator to be used for Single Frequency Networks. The patch also integrated filtering, and a universal hardware driver which provides a logical signal path. The computer running the modulator software was also the network end-point for receiving the ETI feed from the multiplexer. The application was heavily tested on various x86 Intel CPU based computers and it was concluded that most Intel based PCs and laptops on the market are powerful enough to produce the modulated I/Q bitstream in real-time without any problems.

4.5 Others

Many other Open Source programs were used to form components within the chain. Some examples of utilities and programs used for the experimental chain include mbuffer, Icecast2, and netcat.

An open source implementation of a DAB+ encoder named fdk-aac-dabplus is also available. This is a Linux fork of the FDK AAC codec for Android smart phones, which was released by Fraunhoffer IIS. Most manufacturers who build smart devices on the Android platform already hold a patent licence for AAC which covers the use of this code for specific purposes. The software is open source, but commercial use of this encoder for DAB+ services would be subject to IPR royalty payments.

In the experiment, the playout of test material for the multiplex was controlled by a software application called ‘Airtime’. As well as playing out static files, Airtime has the ability to acquire and play out non-linear content such as podcasts. It can also connect to other streams, or accept live feeds and it can make decisions about alternative sources should a wanted one fail. This application is also free and open source. It is developed by a commercial organisation called Sourcefabric, which makes a number of free and open tools for journalism and broadcasting applications. The company generates revenue from its free software through managed, hosted solutions, support and ‘official’ branded media containing the software.

Also worthy of note, but as yet untested, is an API released as open source by Global Radio Labs which enables DAB Electronic Programme Guide feeds to be produced. This API appears to be compliant with ETSI TS 102 818.

Section 5

Hardware

5.1 Modulator

The trial described in this document used SDR technology to generate DAB signals using a commercially available unit from Ettus Research. Ettus is an American company producing Software Defined Radios for academic, industrial and defence applications. Their new B100 unit was selected for the test rather than the USRP1, which had already been proven suitable for DAB in other trials - particularly those carried out by the Canadian Communications Research Centre, and the European Broadcasting Union in Geneva, Switzerland. The B100 unit was chosen particularly because it features external 10 MHz and 1PPS reference inputs as these would be required for synchronising the units for Single Frequency Network operation. It is recommended that this functionality is tested in the future. The new unit was found to be a little tricky to set up for DAB operation initially, but once the software was configured correctly a clean signal was produced. Since the system was built, other lower cost SDR units have emerged which are available at a lower cost than the unit used for the experiment.

The 'WBX'-type transceiver board fitted to the B100 has a wide frequency coverage of 50 MHz to 2200 MHz and it has many features. The RF modulator stage delivers up to 100mW (+20dBm) into a 50 ohm load. In order to allow for the high peak-to-average signal of the DAB COFDM signal, the output was set to less than 5mW to preserve linearity. The DAB signal was very clean with signal-to-noise performance exceeding 54dB when measured 970 kHz from the centre frequency.

5.2 RF Power Amplifiers

Members and associates of the EBU (European Broadcasting Union) have demonstrated a simple amplifier made from a hybrid power amplification module manufactured for mobile radio applications. This module can be operated as a linear amplifier by setting its quiescent current appropriately. Good linearity is essential to prevent distortion of the DAB signal otherwise undesirable IMD products can be generated. For the project described in this document, one of these modules was ordered, together with a suitable power supply, equipment housing, connectors and sundries. An individual with good mechanical skills (and patience) assembled the amplifier, which was then tested for frequency response, gain, and linearity.

The amplifier provided a nominal gain of 34dB and the linearity was such that it could provide a very clean signal up to ~0.5 watts RMS. Exceeding this level caused the COFDM modulation peaks to enter the compression region of the amplifier which resulted in spectral re-growth. This is common in digital transmission, and such products are generally removed from the output of the transmitter by expensive band-pass cavity filters. Although the power module was capable of producing much more power, an objective of the experiment was to keep the costs to a minimum. The additional band-pass filtering required for compliance with the ITU mask precluded the available higher power levels from being used, but the high gain and clean drive made it an excellent pre-driver for a further, more powerful stage.

The prototype amplifier demonstrated that it is not costly or complicated to produce an RF amplifier for DAB which could deliver power levels in the order of 100 watts, however commercial transmitting equipment marketed within the European Union must be certified as being compliant with the Radio & Telecommunications Terminal Equipment Directive. It was therefore important to establish if such specialist certified equipment would be available at a practical cost. As band III is used for DVB-T in some countries it was not difficult to identify a number of suitable amplifiers which are competitively priced. A unit is also under development in Germany by the feilen-stolz partnership with the objective of designing a fully integrated universal transmitter and gap-filler specifically for FM/DRM and DAB applications.

5.3 Filters

Filters that remove the unwanted spectral re-growth from digital transmitters (such as the one in Figure 1 below) are mechanically complex, heavy, and expensive. These are used widely in existing DAB signal chains as the signals that leave the transmitters would not in themselves be compliant with the ITU mask. This is due to spectral re-growth that occurs within RF power amplifiers. This might not be the case for low power *standalone* transmitters, or for coverage enhancing (gap) fillers in Single Frequency Networks. The re-growth occurs due to high level signal peaks running into the non-linear operating (or compression) region of the amplifier. COFDM modulators often modify the output envelope to reduce this effect though a process known as pre-correction, or pre-distortion This is a technique which increases the useful output power by significant margins while the same time increasing power efficiency.

The software modulator used in the experiment described in this report is basic, and it *currently* has no pre-correction. It was decided that instead of trying to squeeze the last few watts out (and then have a need to clean it up afterwards) the final amplifier would be run more than 6dB below the rated output. It might seem inefficient to design an RF transmission stage using expensive parts and run it ‘light’, but the additional cost of the power devices is still far less than the cost of the cavity filters that would otherwise be required, at least up to power levels of around 100 watts. The over-rated RF devices also make for a reliable design and the loss in efficiency is not significant at low power levels. Less complex (and therefore much less expensive) filtering may then be employed to attenuate any residual ‘shoulders’ where necessary.

Fig 1: Shows a typical medium power 'battery' of six cavity filters fitted after a DAB transmitter. De-rated transmitter power amplifiers can reduce the need for these large filters. At low power levels the power efficiency reduction is unlikely to be a concern.

5.4 Aerials

A wide variety of standard designs of aerials for low power applications are available from a number of manufacturers which cover band III and many stock patterns are available to suit different coverage requirements. The cost of such aerials is the same as those commonly used for FM broadcasting. For the purposes of the experiment, a standard three element Yagi was used. The aerial was installed pointing due north towards the South Downs to provide terrain screening and to constrain propagation of the signal up and down the coast. This configuration also avoided unnecessary overspill towards France. A NEC antenna pattern prediction model showed the signal to the east and west was 10dB down on the main, northerly lobe. Figure 2 shows the aerial as it was installed on the mast. Unfortunately, roof access and frequent mast visits were not very practical. It had been the intention to look into the possible benefits of using circularly polarised transmitting aerials for DAB. It is recommended that a follow-on study should be carried out on this subject.

Fig 2: The three element Yagi mounted at a height of 4.4 m on the mast. The parabolic dish provided a reliable 1km IP link over Wi-Fi (100mW ERP).

Section 6

Testing

6.1 Transmission Chain

At the heart of the Brighton experimental multiplex was a PC running a customised version of xubuntu, which is a derivative of the Debian Linux operating system. The appropriate software was compiled from source code and the operating system was then tuned for best performance. The installation was re-mastered onto a DVD to allow the customised platform to be easily installed on a number of desktops and servers which had been acquired for the necessary testing and development of the platform. An old 2 GHz dual core Pentium computer was selected to be the test ensemble multiplexer, and a shell script was written to define the services. The transmission site was a residential tower block that also houses the transmitter of a local FM broadcaster (which was useful for coverage comparison purposes). A tank room beneath the roof housed the DAB equipment.

The transmitter consisted initially of a Lenovo N500 laptop running the customised Linux operating system this received the ETI feed via a Wi-Fi link and then produced the modulated DAB signal. Later, both of these PCs were replaced by a single ‘server grade’ computer which combined all of the network elements (encoding, multiplexing and modulation) in just 1U depth of the rack. In the fully integrated test, the ensemble services were acquired via a public Internet connection. The Ettus Research B100 transceiver card fed the custom 0.5 watt driver, which in turn drove a final power amplifier. A three element Yagi aerial pointing north was installed on the rooftop mast.

6.2 Test Equipment

As the DAB tests were initiated by the author as a personal project, there were severe constraints on time, budget, and test equipment. In addition to the typical engineer’s toolbox, a calibrated Agilent ‘Field Fox’ was acquired on loan for commissioning measurements and adjustments to be made from time to time. An EME directional coupler was fitted to the aerial feeder cable to allow the return loss of the feeder, and the spectral purity of the transmitter to be monitored.

A time-limited trial version of a software reference receiver (DAB Scout 2, see figure 3) from Rundfunk Technische Institute proved to be very useful as a test set for confidence checking the multiplex configuration and as a reference receiver. The Scout software uses a specific USB stick as a ‘front end’ which is normally intended for DVB-T reception. In addition, Scout provides a useful signal strength indicator that is also able to display the signal-to-noise ratio, which is useful for detecting elevated levels of man-made noise. The pre-viterbi error rate was also available for confirming that the transmitted signal was error-free at source.

Five different consumer DAB receivers were used to ensure that no ACI problems existed in or outside of the transmitter site building, and also for a confidence check that there were no subtle problems with the multiplex configuration. In the initial vehicle drive tests, an Advantest R4131B spectrum analyser was used for visual signal checks. A final measurement campaign was carried out using a RadioScape measurement set.

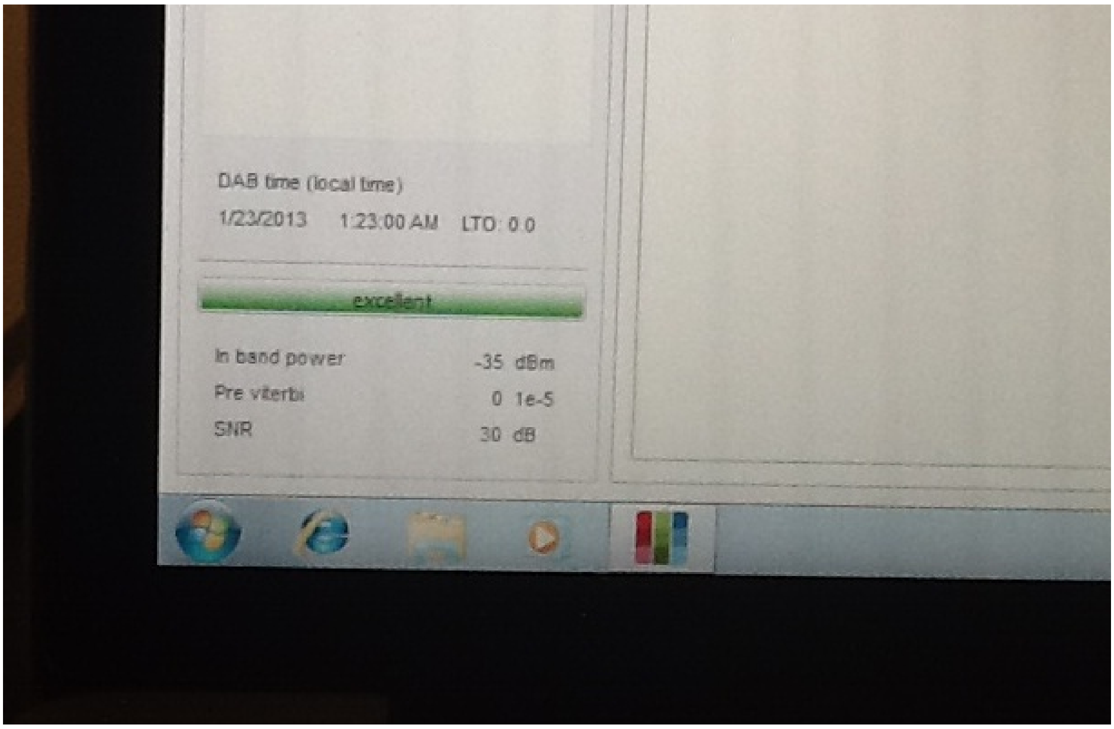

Fig 3: IRT DAB Scout reference receiver showing off-air reception at the site with full signal, maximum SNR and zero BER.

6.3 Mp2 Comparisons

The quality achieved in DAB transmissions will depend on the sampling rate and bitrate used to code the services and also the technical quality of the encoder. An interesting finding made through listening tests in this trial was that some services currently on DAB seemed to have subjectively poorer sound quality than might be expected for the bitrate used. The services were checked against two different benchmark coders - the test bed and the control sources were checked several times for anomalies, but none were found. There are a few possible explanations for this, including non-linear programme source material or poorly implemented audio pre-processing. There may be factors unknown to, or outside of the control of the broadcaster, such as incorrect choice of psychoacoustic model in the mp2 source encoder, a poorly implemented encoder, excessive use of X-PAD data (which would use capacity otherwise used for the audio payload) or a combination of the above. The possibility exists that concatenation or transcoding is occurring downstream of the broadcaster which could be affecting the audio quality. The open source tools tested in this project are an excellent resource which can help broadcasters in creating quality benchmarks, which in turn can be used by them to ensure that the technical quality of the transmitted audio is as good as it can be.

Although there is no substitute for delivering ‘high quality’ by using appropriate bitrates, it is apparent that there is room for some improvement in the subjective sound quality of some services currently on DAB in the UK by addressing all of the factors described above. The listening tests were made through off-air comparisons with the existing DAB multiplexes along with the experimental multiplex source encoder (TooLAME). Several sets, including a reference receiver, were used. Additionally an old ITIS D-ACE DAB source encoder and service multiplexer was used as a second benchmark encoder/decoder.

6.4 Ensemble Topologies

In large DAB networks, each broadcaster typically encodes their programme at their studio, and a circuit (typically ISDN) then conveys this to a central multiplexing centre. From the multiplexing centre, the output Ensemble Transport Interface (ETI) feed is distributed to the various transmitter sites via relatively expensive G.703 circuits and microwave radio links. Some transmitter sites may also need redundant backup circuits, adding to the distribution costs significantly.

Recognising that a single transmitter multiplex can be configured in several different ways, various topologies were tested in this trial to consider the pros and cons of each.

In a typical network configuration, the multiplex is a central point to which all services are delivered. This affords easy access to the physical hardware that provides various connection options in addition to IP. Direct access to the physical hardware also assists serviceability, and hence availability – assuming suitably skilled personnel are available. This also requires the most bandwidth of the network options because a high Quality of Service is needed to carry the multiplexer ETI output to the transmitter. The contribution feeds arriving at the multiplexer also need to be received with a high degree of reliability.

The second configuration tested was co-location of the multiplexer at the transmitter site. This topology enabled low cost broadband connections to be used to securely receive just the contribution feeds. Distribution of the multiplexer output was straightforward because of the direct connection to the transmission equipment and the configuration proved to be very reliable. Remote access only was possible and so physical access would have been required if a fault condition arose. Naturally, if the studio and transmitter were co-located, then this would be much less of an issue.

Another configuration was tested where the multiplex was operated ‘in the cloud’ during the final two weeks of the test - this also delivered impressive results. A low cost virtual private server (VPS) with suitable connectivity was customised giving it flexibility to draw Internet streams, or receive contribution links and a TCP/IP server application installed for distributing the ETI feed to the transmitters. Due to the high bandwidth environment and being close to the backbone (which reduces the number of router hops to the sources), all contribution feeds were stable. In addition, as the ETI server supported multiple TCP connections, it was subjected to additional load using the free OpenMokast ETI decoder application. This software application was used extensively for monitoring and a variety of testing purposes. This load-testing proved in principle that such a VPS could potentially be used for distribution of the ETI to multiple transmitters if this were required for particular applications. This does entrust the system availability to a third party, and requires investment in ensuring that security is adequate, although these concerns could be ameliorated to a degree by selecting two different providers on completely separate network infrastructures. The same approach of using two different broadband connections at the transmitter site would increase the availability of the ETI feed to the transmitter in the case of a fault with one provider.

Each of the above arrangements has pros and cons. It is good engineering practice to duplicate mission-critical network elements, so a combination of the above approaches is likely to be best - a pair of multiplexers with one residing at the transmitter site and the other at a central point, or in the cloud. Multiplexes can be configured to cascade into others, or failover, or both, so there is plenty of flexibility to suit most situations. In addition, the open-source software gives the operator the freedom to run instances of any of the network elements anywhere, and at any time without software licences fees being incurred by so doing.

6.5 ACI Investigation

Adjacent Channel Interference (ACI) was thought to be a potential issue for the test. The concern was serious enough that the test was constrained to operate at low power levels. Because of this concern, rigorous checks were made to ensure that the test would not cause any disruption to the reception of broadcast DAB services in and around the transmitter site building. Because the area is very densely populated, a recorded loop with contact information was transmitted constantly. The purpose of this was to enable any member of the public not able to receive all the broadcast DAB services to (albeit unintentionally) discover the recorded loop upon performing a re-scan. Five different receivers were tuned to each of the available multiplexes in several locations, and a battery powered DAB radio allowed a walk-around test of reception. One of the checks was made ~7 metres beneath (but slightly forward of) the transmitting aerial where the given 45dB protection ratio for the three-block spacing would certainly have been violated.

Fig 4: One of the ACI checking receivers showing perfect reception of the BBC multiplex ~7.4 metres away from the transmitting aerial. The BBC transmitter was 3.3 km distant.

Attenuation by the building fabric would have a similar impact on the levels of the potential victim signals. The nearest site (Whitehawk Hill) was 3.3 km distant, but a line-of-sight path resulted in the received signal being quite strong. Inside the building, the signal from Whitehawk Hill was variable, but no ACI was detected. This confirms that low power transmitters will not damage the coverage of other services transmitted from elsewhere providing that the field strength of the other wanted signal is of sufficient magnitude.

In the future, further investigations should be carried out to determine the relationship between the field strength of the victim service(s) and that from a low power transmitter. Currently, it would seem that a little more investigation on ACI blocking could deliver more flexibility when planning standalone and SFN enhancement transmitters than the currently agreed industry MoU on ACI provides. It is possible that a new exemption guideline for low power transmitters could be determined under certain circumstances.

6.6 Transmission Mode

All current UK DAB services use transmission Mode I, but the use of transmission Mode II was intended for use with Band III local radio as well as L Band. Mode II uses fewer carriers (384) and has a shorter guard interval than Mode I. in the tests, the use of Mode II was found to have interesting effects on a number of DAB receivers (which are detailed in the section on receiver behaviour) but no advantage was found in using it at this site. In fact Mode I seemed to give a slight performance advantage on coverage robustness. Mode I also generated fewer third-order IMD products* within the transmitter. No further investigation was considered necessary and Mode I (1536 carriers) was used for the remainder of the experiment. Once additional equipment has been sourced, an investigation should be carried out to determine if mode II with carrier offsets would be of any benefit for co-block operation.

* This may in part be due to the modulator design but is possibly also a consequence of there being more energy in each carrier (due to there being far fewer of them) than in Mode I.

6.7 Receivers

During the course of the project, a number of different receivers were tested and these were tuned to the multiplexes receivable in the area as well as the low-power test transmission (in Modes I and II). The latter mode was found to offer no technical advantage with the configurations tested in the experiment although further tests are recommended

Although it was decided not to continue with the Mode II comparison for this experiment, the effect of this mode on DAB receivers is still worthy of mention. One early design of receiver could not detect a Mode II signal. These sets were originally expensive, and were constructed in such a way that many are likely to be in serviceable condition for some time. As replacement of radio receivers is a relatively low priority in many households, they are expected to be in use for many years. A large number of DAB receivers based upon two different chipsets also seemed to exhibit a common problem with the signal indicator when Mode II was in use.

It became apparent that there is a lack of consistency in performance and behaviour between different receiver models. The user interface on some receivers was not intuitive, and some were quite ‘fiddly’ to use. It had been assumed that receivers from different manufacturers, which made use of the same DAB receiver module, would deliver comparable reception quality, but this turned out not to be the case. RF sensitivities were variable, and ‘buggy’ features made some sets stand out as being more problematic than others.

No in-depth investigation of receiver sensitivity was carried out but it is suspected that different approaches to layout, screening, power supply design, the display etc result in different levels of self-interference within the receivers themselves. There didn't seem to be any correlation between receiver price and RF signal performance, with one of the worst performing products being a premium receiver, and one that offered the best sensitivity (but was found to be monophonic) was acquired from a supermarket for just £17

A further concern was that a few of the older receivers could not decode a DAB service of more than 140 Capacity Units (CU). Protection levels UEP1 and UEP2 can be used to slightly enhance the robustness of DAB transmissions by increasing the quantity of redundant data. This increases the number of units that a DAB service uses. The vehicle drive tests demonstrated that these modes do help to reduce drop-outs in areas of low signal (caused by building obstructions) particularly with mobile reception rather than when static. The 140 CU limitation restricts the bitrate that such a higher-protected service can use if reception was required on these less capable receivers. The maximum bitrates that these receivers can decode are 128kbps at UEP1, 160kbps at UEP2 and 192kbps at UEP3. It is not known how many of these problematic receivers are in circulation, but two were encountered during the trial. An isolated problem was also found with an early in-car adaptor that was found to be incapable of tuning to the lower frequency blocks, so the test multiplex could not be received with this device.

Finally, one pocket DAB receiver was found to provide a remarkably short battery life – it also had no socket for a charger. New alkaline batteries provided around three hours of listening, and the surface-mounted headphone socket became separated from the receiver's circuit board after a few weeks, which indicated that not only was the design poor, but the build quality was also poor.

The variation of sensitivity and capability (with no easy way to discern the good from the bad) clearly supports the need for a 'kite mark' standard for digital radio sets as intended in the new 'digital tick'.

Section 7

Coverage and Planning

7.1 Test Coverage

The aerial system was designed to be directional to constrain the signal from the test transmitter to the immediate urban area while keeping overspill to the east and west to a minimum (as there was no terrain limiting). The aerial system and metallic objects within close proximity (including the supporting mast structure) were modelled in the NEC antenna design tool in order to determine the antenna's precise gain, and directionality. The HRP and VRP characteristics are shown in figures 5 and 6. This data was then used to carry out the coverage prediction seen in Fig. 7.

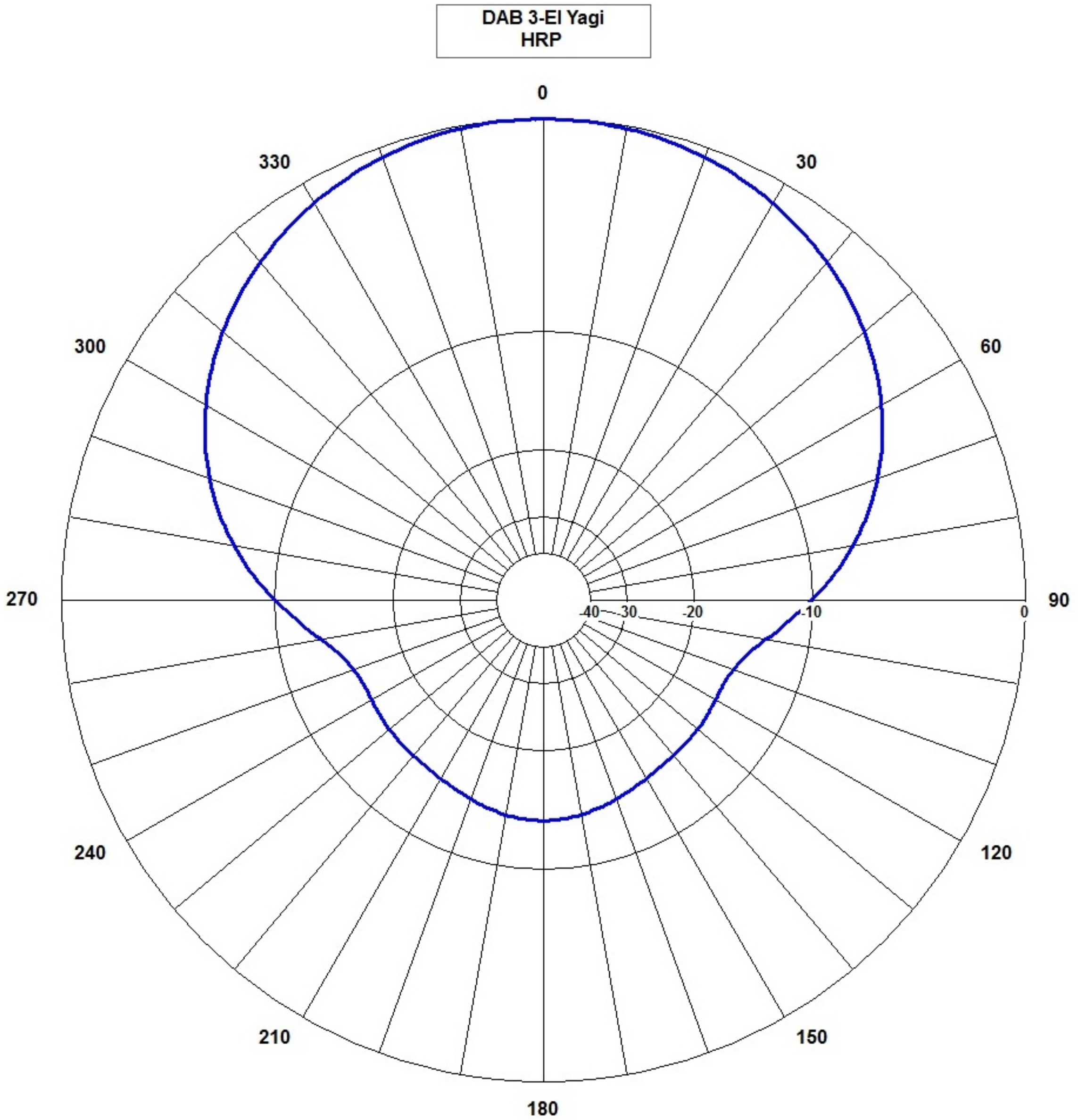

Fig. 5 – NEC model of the Horizontal Radiation Pattern. Note that the pattern was 10dB down to the East and West.

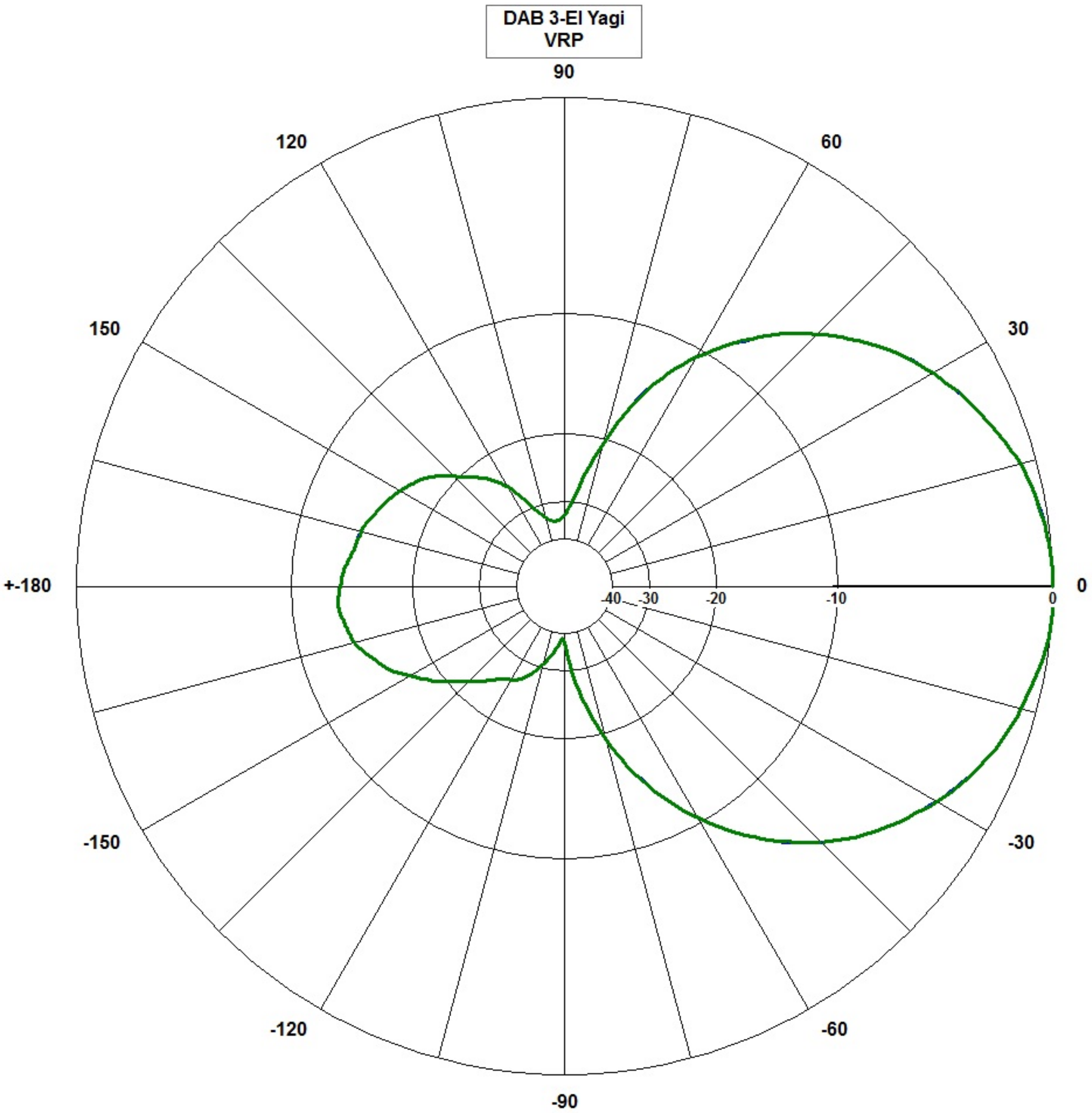

Fig. 6 – NEC model of the Vertical Radiation Pattern. Mechanical down-tilt could be used to increase close-in field strength to augment indoor reception while at the same time reducing outgoing interference.

The predicted coverage was then compared to the results of a vehicle drive campaign – the interpreted results are shown in figure 8. The route driven was predominantly along main roads that were surrounded by dense building clutter and most of the route did not have direct line-of-sight to the transmitting site. It can be seen that the coverage prediction does show where difficult reception areas would be with a good degree of accuracy when correlated with the measured data. Several hours of additional drive testing were carried out and the sound and video of the surroundings were recorded. This proved to be useful as the visual record of the surroundings where dropouts occurred provided a means to help identify the likely cause later. A Ford Focus fitted with a stock DAB/DAB+ radio was used for the drive tests.

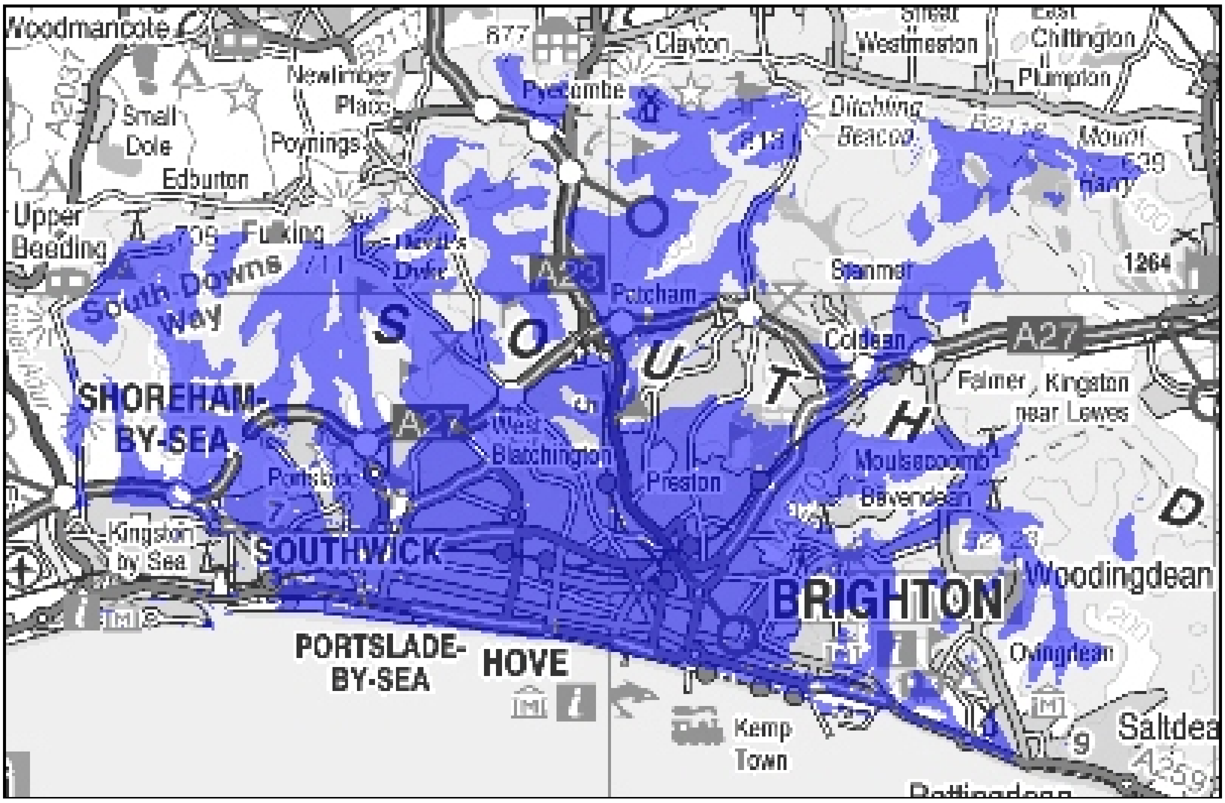

Fig. 7 – The Predicted terrain-limited coverage, for a received signal of 58dBµV/m or better.

Fig. 8 – Mobile measurement route – reception was available at all logged points. The colours denote the field strength, adjusted to the likely indoor field strength. Green=58dBµV/m, Orange=52dBµV/m, Red=42dBµV/m.

7.2 Spectrum Availability

While spectrum availability has not yet been extensively studied, it is likely that frequency blocks could be identified in many areas for transmitters radiating power levels in the order of 100 watts or so. In some locations it may be possible to re-use existing DAB frequencies, in coastal regions it may be possible to re-use the blocks of neighbouring countries and in others areas there could be options within cleared PMR spectrum. In the majority of cases, the low power services would need to accept higher than ideal levels of interference that would limit their coverage areas and outgoing interference would also need to be constrained.

7.3 Service Planning

Once a target coverage area and frequency resource has been identified, it is important to ensure that the opportunity for block re-use is optimised by constraining unwanted overspill of coverage. One approach could be to draw a polygon around the served urban areas and to draw a median line between adjacent polygons. A field strength limit could then be placed on the lines. For example, it might prove acceptable to place a limit so that the 1% time field strength does not exceed ~40dBµV/m over a significant area beyond the lines between co-block areas. There is also the option of planning coverage to overlap between adjacent multiplex areas where contiguous coverage is desirable and where different blocks are available to form a 'lazy MFN'.

Meeting tight coverage limits is not as onerous as it can be in Band II. It is easier to engineer practical aerials to exhibit much tighter radiation characteristics in Band III due to the shorter wavelength. Electrical or mechanical beam tilt can be used to enhance field strengths in the core coverage area and minimise overspill by lowering the angle of maximum radiation to below the horizon. Ensuring good design and engineering practices would maximise frequency re-use opportunities as well as making international coordination of such services simpler.

Transmitter sites would need to be carefully selected so that they are close enough to the core coverage area to provide satisfactory in-building reception while ensuring that they do not create ACI/blocking to the coverage of other services. Ideally, small scale DAB services would share the same transmitter sites, or ones nearby to, the national and local DAB services with coverage in the area.

As the DAB standard was designed to suit mobile and portable reception, DAB currently radiates in the vertical plane only (vehicle and portable antennas are vertically polarised). One objective of the experiment was to test the use of circular polarisation for transmission in order to measure any enhancement of coverage within the service areas. It is thought that a circular component might help to enhance reception in dense urban clutter due to the multipath environment being different in each plane of radiation. The hypothesis is that the resulting reflections would be sufficiently different that this might increase the percentage of locations served. Unfortunately the experiment ended before the opportunity arose to carry out this work due to roof access restrictions. It is recommended that further studies be carried out to determine if there is merit in using mixed, or circular polarisation in single transmitter multiplexes and in particular, to study the effects on indoor reception.

Section 8

Potential Uses and Conclusions

8.1 Uses

Small scale DAB has the potential to be a technology that could deliver social gains similar to the current community radio model. It could also help to avoid the creation of a digital divide – especially in areas where there is significant diversity or hardship. It could be used to provide a digital platform for smaller services such as (but not limited to) student, educational, ethnic and specialist interest groups. Another potential use is for 'ad hoc' services as a digital equivalent to RSLs. Such an opportunity would be particularly useful in areas where the FM band is congested, and where as a result, contention on the frequencies that can be used for RSLs occurs.

Such an approach to digital radio could also provide an attractive incremental platform for innovative radio that currently is more likely to exist only on the public Internet. It might be argued that DAB should be accessible by these 'community' broadcasters. Compelling, locally relevant, and conveniently accessible services on the DAB platform could provide additional inclusiveness. Current DAB receivers may not appeal to certain groups of listeners because some existing receivers are technologically unremarkable when compared to a modern smart phone or tablet PCs. Two row alpha-numeric text-only displays are rather modest, and are likely to be particularly uninteresting to the younger age groups. Therefore, the availability of compelling local content targeted at these audiences could potentially help overcome their concerns about the technology in the receivers.

Additionally, small scale DAB could also help to address hurdles currently presented to 'small stations', and enable them to gain a foothold on the platform. Many such stations do not currently have a digital radio option that would preserve the localness of their coverage area, nor one that is financially sustainable – even if sufficient capacity were available on a local multiplex. Pressures on available capacity are currently such that there already is a downward trend in audio service bitrates. Existing local networks serve relatively large geographical areas and the associated costs of carriage on them are very high when compared to the operating costs of a single 100W ERP FM transmitter. The WorldDMB 'Eureka!' publication of February 2013 indicated that DAB has ten times greater power efficiency when compared to FM, but DAB networks utilise several transmitters, each needing cabin space, electrical power, mast aperture, telecom or microwave circuits (for programme feed) and maintenance. This goes some way towards explaining the large cost differential between FM and DAB. Small scale FM stations spend circa £10,000 per annum on FM transmission which is many times less than the current DAB network carriage costs - even for a low quality monophonic digital service.

Although DAB is currently an unsuitable replacement technology for these small scale FM broadcasters, for the future to be a predominantly digital one, FM listening will decline over time. The previous, natural migration path from low fidelity AM to stereophonic, wide audio bandwidth FM will be followed. If this is to be the case, then these broadcasters (who currently provide valuable local services) ideally should not be excluded from the future radio broadcasting landscape - particularly at a time of consolidation by both the BBC and the commercial operators, who previously had both generated more locally focused content.

Small-scale multiplexes would enable the smaller stations to gain a presence on the digital radio broadcasting platform at good quality without increasing their transmission costs to unviable levels. Few small broadcasters find the larger multiplexes attractive, particularly at a time when many stations are struggling to break even. Such small-scale multiplexes would also have the desirable effect of introducing choice in carriage that might ameliorate problems associated with the lack of supply-side substitution as well as a remedy to bitrate capacity pressures and inefficient overspill coverage of small stations.

Small-scale DAB is a solution which removes financial barriers to entry and avoids wasteful overspill coverage - particularly for multiplexes that currently have bitrate capacity pressures. When referenced to a single transmission site and a power of up to 100 watts ERP, the operating *cost* price per Capacity Unit is estimated to be below £10 per year. As each multiplex provides precisely 864 units, this translates to an approximate baseline cost of £1400 per annum for a near-FM quality service at 160 kbps, UEP2.

This rough calculation is based upon distributed overhead costs and includes rent, circuits, electricity and technical maintenance. The estimated operating cost of an entire multiplex is not significantly different to the average cost of operating a single FM transmitter. It is expected that small-scale multiplexes might carry a variety of different services between which the operational costs could be shared. Keeping digital overheads manageable and sustainable for broadcasters is essential in order for listeners to grow their interest in DAB.

If small FM broadcasters (be they community, or commercial) were to become the operators of such small-scale multiplexes, this could generate modest revenue streams for them (rather than becoming an additional operating cost). This income could be realised from the sale of surplus capacity. In theory, some capacity could potentially be traded with other multiplex operators to form 'digital islands' of coverage to target demographically relevant coverage, or serving adjacent metropolitan areas while controlling unwanted overspill coverage – a spectrally efficient approach with direct benefits to citizens and consumers through easily accessible local content, and at the same time providing a broadening of choice. The island model on the other hand could also encourage cannibalisation of capacity that could otherwise have been used by some local services. Some, or all, of the capacity could be reserved for content originated within the coverage area of the multiplex.

8.2 Conclusions

The experiment demonstrated that a stand-alone Software Defined Radio approach to DAB multiplexing and transmission can deliver high availability and high quality results at costs that are near to parity with an FM transmitter system carrying a single service. Coverage was broadly as predicted meaning that standalone transmitters do not need to be planned in a significantly different manner. Propagation in band III is different to band II (being an octave apart in frequency) which means that even when co-sited with a band II FM transmitter, identical coverage cannot be guaranteed. Mis-matches might not be resolved through increasing transmitter power alone because of the resulting increase in outgoing interference. It is recommended that an investigation should be carried out into circular polarisation operation to determine if this has any effect on the robustness of indoor reception where a single transmitter is used.

The Brighton experiment demonstrated in a real world environment that it is possible to deploy a small scale DAB multiplex without creating ACI problems if the transmitter is placed in an area where the field strength from other 'wanted' multiplexes is already high. The costs for operating an entire multiplex are comparable to those incurred in operating a small scale FM transmission system. No difficulties are anticipated in finding usable frequency blocks in most areas with a low opportunity cost although further work is recommended in this area.

Section 9

Credits

In addition to my colleagues, I would very much like to extend my thanks to a few friends who contributed towards various key aspects of the experiment:

Kerry McCarthy: who inspired me to think differently about DAB, for recording the ensemble system messages, and for providing music for the subjective testing.

Mike Craig: for turning my pile of components into a fine RF power amplifier for the project, for the loan of various leads, loads and other bits and pieces, and for the initial confidence drive tests.

Daniel Nathan: for kindly donating the use of his mast. I doubt the project would have got off the ground without it.

Martin Spencer: for his assistance with the aerial installation, and for mucking in with everything from drive testing, supplying couplers which I had forgotten, and for providing some of the test equipment, and the larger prototype amplifier.

A final, very special thanks to the coders: Pascal Charest and Francois Lefebvre (authors of mmbtools), Mathias Coinchon (Python UHD player), Matthias Brändli for his (SFN and UHD patches).

Acronyms

ARM	Advanced RISC Machine
AAC	Advanced Audio Coding
ACI	Adjacent Channel Interference
COFDM	Coded Orthogonal Frequency Division Multiplexing
DLS	Dynamic Label Segment
DMB	Digital Multimedia Broadcasting
DRM	Digital Radio Mondiale
EBU	European Broadcasting Union
ERP	Effective Radiated Power
E1	2048kbps fixed time division multiplex telecoms circuit
ETI	Ensemble Transport Interface
FIDC	Fast Information Data Channel
HRP	Horizontal Radiation Pattern
IMD	Inter-modulation Distortion
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISO	International Standards Organisation
ITU	International Telecommunications Union
kbps	Kilobits per second
MoU	Memorandum of Understanding
MFN	Multi-Frequency Network
mp2	Moving Pictures Expert Group Layer 2 audio
NEC	Numerical Electromagnetics Code
PAD	Programme Associated Data
PAPR	Peak-to-Average Power Ratio
PMR	Private Mobile Radio
R&TTE	Radio & Telecommunications Terminal Equipment Directive
RSL	Restricted Service Licence
SDR	Software Defined Radio
SFN	Single Frequency Network
UEP	Unequal Error Protection
VPS	Virtual Private Server
USB	Universal Serial Bus
VRP	Vertical Radiation Pattern