Small scale DAB trials

Annex 2: Technical background and architecture

Research Document

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About this document

This document accompanies Ofcom's final report on the small scale DAB trials. It provides a more in-depth technical account of the development of a 'production ready' DAB platform based upon common, off-the-shelf computer hardware running Free and Open Source Software.

This document is primarily aimed at a technical readership, and assumes familiarity with the DAB technical standards and radio engineering techniques

Contents

Section 1

Introduction

1.1 The small scale DAB trials are based upon low cost hardware and open source software. In this document we describe the components of the small scale DAB transmitter systems used in the trials, and some technical lessons we have learned during the course of the three separate types of trial.

1.2 The main functional components of a typical system are audio encoding, multiplexing, modulation, power amplification, filtering, and a transmitting aerial, and these are illustrated in the diagram below.

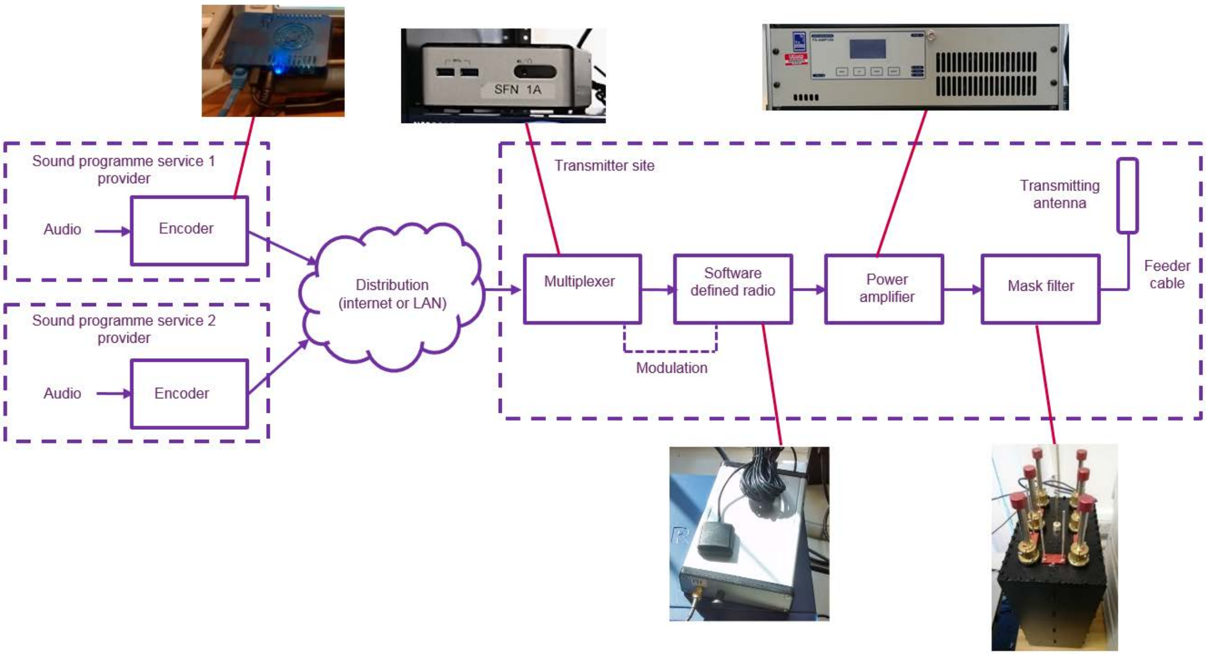

Figure A1: Typical small scale DAB system block diagram

Section 2

Encoding

DAB encoder

2.1 The initial Brighton small scale DAB trial of 2012/3 used the open source toolame 02l Layer II audio codec, which had been unmaintained since 2003.

2.2 Open Digital Radio (www.opendigitalradio.org, ODR) is a not-for-profit organisation based in Switzerland whose purpose is to develop software tools which aim to make it easier to access digital radio broadcasting technology. ODR adopted the abandoned toolame source code and developed a new 'fork' (independent development) of the software in order to adapt it further with the aim of making it more 'user friendly' for broadcasting use.

2.3 The toolame application supports all valid sampling and bitrates and comes with a selection of tuned psychoacoustic models in addition to the original ISO MPEG working group Dist10[1] reference implementation. These additional models enable further optimisation of quality to suit different output rates. The sonic differences between the models are notable, so it is critical to select the appropriate model to optimise the sound quality. Mono, joint and full stereo modes are all supported.

2.4 The ODR fork of this code (named toolame-dab) has been enhanced with the addition of a flexible input library (libvlc) which provides the 'glue' between the application and many different kinds of audio sources. There is also an input for text and images to be transmitted inside the frames as Programme Associated Data.

2.5 Outputs can be saved to a file, or sent to multiple remote destinations via IP. When the encoder application is sending data to the multiplexer, a distributed transaction protocol called zeromq is used. One useful feature of zeromq is that it supports a layer of elliptic-curve cryptography which provides optional authentication and security. Encryption keys are generated on the multiplexer; these are then loaded on to the authorised encoders manually before they are deployed.

2.6 The audio encoding units supplied to small scale DAB trial operators supported MPEG-1 Layer 2 audio only, but could also deliver DAB+ bitstreams by loading an additional software application. An important design consideration of the trial systems was that they should be of the lowest technical complexity possible, as it was assumed that mostly inexperienced operators would be using the system.

Multimedia Object encoder

2.7 Both the DAB and DAB+ encoders support the transmission of Programme Associated Data via a Multimedia Object Transfer helper application developed by Italian research organisation CSP[2]. This is used in conjunction with the encoder application, which together enable an X-PAD (EN 301 234[3]) transmission of Dynamic Label Segment (DLS) text data and/or multimedia objects such as images.

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[1] Downloadable from ftp://ftp.tnt.uni-hannover.de/pub/MPEG/audio/mpeg2/software/technical_report/dist10.tar.gz
[2] www.csp.it
[3] http://www.etsi.org/deliver/etsi_en/301200_301299/301234/02.01.01_60/en_301234v020101p.pdf

2.8 During the development phase of the project, Ofcom selected and built replicable systems for both ARM and x86/64 platforms. A micro SD card image was prepared for the Beaglebone, Raspberry Pi, and Odroid C1, U3 and XU4 single board computers. The Odroid U3 and Odroid C1 were initially selected for deployment during the main trials, and over sixty units were prepared on the assumption that each trial might carry up to six services unique to that particular multiplex. Trial operators were encouraged to provide additional encoders as required, and invited to use the units provided as a template.

2.9 The encoder parameters and destination IP address are configured by connecting a display and keyboard to the encoder or by using a secure terminal program. The operating parameters are contained in a simple script which can be edited manually to make changes. The script also places the encoder in a controlled loop to enable automatic recovery in the event of accidental disconnection or replacement of the sound input device.

2.10 During the course of the trials, an ODR user in France released a helper application based on 'Supervisord' called 'ODR Encoder Manager'[4]. This enables the setting of all parameters, and the addition of multimedia objects, via devices on the same network segment using a web interface. The ODR Encoder Manager has an API, and the Dynamic Label Segment text and multimedia (slideshow) content can be updated automatically from the studio playout and automation software. The encoder manager was developed after the encoder design for the trial was frozen for release. Therefore, the trial units did not contain the web configuration option.

Encoder hardware

2.11 'Smart device' development has led to the availability of small form factor, low-cost yet relatively powerful single board computers. Most of these development platforms use ARM processing cores optimised for battery powered use, so they use very little electricity when compared to a typical home or office desktop PC. These ARM cores had already been used by Ofcom engineers to form building blocks of the DAB platform, and their potential had been established. The Raspberry Pi computer was initially used as our main encoder development platform, but this was later superseded by the Odroid U3 and the Odroid C1 because of some storage media compatibility issues experienced with the Pi.

2.12 It was planned that up to six source encoders would be provided to each of the ten triallists. It would not have been practical for us to provide audio encoders based on desktop PCs or low-powered 1RU servers due to storage and working space constraints. It was therefore decided that only ARM single board computers would be used for encoding. A quantity of Odroid U3 and Odroid C1 units were procured, and fitted with suitable SD cards or eMMC modules which we had prepared by copying the operating system and the DAB encoding applications on to them.

2.13 It was later found that one of the models of single board computer would freeze unpredictably. This problem was eventually traced to a combination of a power supply smoothing issue on the board, along with poor quality USB On-The-Go (OTG) cables which exhibited a high series resistance (and which resulted in a significant voltage drop on the USB 5 volt rail). The USB OTG cables had been procured as they were needed for the sound input devices due to a different, but well understood, limitation with the full size USB ports on the single board computer. We observed a pattern whereby certain encoder installations experienced seemingly random

[4] https://github.com/YoannQueret/ODR-EncoderManager

failures, while others had this type of encoder in operation with no such behaviour being experienced. The alternative single board computer units were no longer in production so the Odroid XU4 (a newer, more powerful unit) was offered as a replacement for any troublesome units. The replacements have subsequently proven to be very reliable in service.

2.14 The lessons learned from this experience are that single board computers consume little power, and with careful hardware and peripheral selection they can be used as a reliable, low cost encoding solution that takes up very little physical space. Using desktop or industrialised computers could be an alternative approach given their more predictable performance, their robust construction, and their wide availability and interchangeability.

Input audio signal conditioning

2.15 Radio broadcasters use dedicated audio processing units to control dynamic range and to create a ‘signature sound’ for their stations. These units prevent undesirable overload distortion and can also correct low audio levels. A small number of audio levelling units were procured and distributed to triallists in case they encountered problems with audio level control, or maintaining level consistency between different services in the ensemble. These units do not employ aggressive multiband compression and it was found that as well as providing consistency to the programme levels, there was a noticeable reduction in audible encoding artefacts. If a more powerful PC architecture were to be used for encoding, it may be practical to integrate audio level control within the encoder as another software application.

Sound interface devices

2.16 Many different sound devices are supported in the Linux kernel, so the primary consideration was to balance cost and quality. A £25 semi-professional unit was selected which provides good analogue audio performance (equivalent to some units costing several times more). Many small stations have studios which mix audio in the analogue domain, and this was the interface of choice for the majority of services carried on the trials. Using analogue audio avoided potential problems caused by clocking and sample rate mismatches which can sometimes occur when interfacing different equipment in the digital domain. An S/PDIF digital audio interface was also tested and was used by some services. This interface also accepted AES3 (AES/EBU) bitstreams, when carefully unbalanced and level adjusted. The digital sound device was roughly the same cost as the analogue device and it provided a clearly audible improvement in audio quality – especially when fed from an entirely digital programme chain.

DAB+

2.17 DAB+ employs the HE-AAC audio codec which requires approximately half of the data rate for similar subjective performance to an appropriately optimised MPEG-1 Layer 2 codec. The codec offers a greater choice of sampling rates, and other extensions which can be used to enhance subjective quality when used for bandwidth sensitive applications like broadcasting and streaming. One such technique is called Spectral Band Replication. SBR is used by halving the AAC sampling frequency, and replacing the high frequencies with instructions which enable the decoder within the receiver to artificially reconstruct the high frequency sounds.

2.18 An additional technique which further reduces the overhead is parametric (or synthetic) stereo which provides additional rate savings beyond what can be achieved with the common ‘joint stereo’ modes in other codecs. This involves running the AAC core in mono. Parametric Stereo uses similar techniques to SBR to send positional information which the decoder can use to reconstruct the stereo image.

2.19 HE-AAC also employs an additional layer of Reed-Solomon error correction which can help to improve reception, which is a particularly useful property for small scale multiplexes. Subjective listening tests indicate that HE-AAC can deliver good quality stereo audio at around 80 kb/s. It is also capable of delivering lower fidelity stereo at lower rates than Layer 2 through the use of parametric stereo and Spectral Band Replication.

2.20 The first regular use of DAB+ in the UK was introduced by Solent Wireless, who operate the Trial Portsmouth multiplex. Their technical partners, Commtronix Limited, became holders of a unified AAC licence through VIA Corporation (the company which operates a patent pool on behalf of the intellectual property rights holders for AAC). The technical partners subsequently supplied encoders to services on other trial multiplexes who wished to broadcast using DAB+.

2.21 Because the DAB+ codec provides acceptable sound quality at lower bitrates than the DAB codec, it has been used to relieve ‘congestion’ on some trial multiplexes. Because carriage costs for DAB services are generally proportional to the capacity resource occupied on a multiplex, a DAB+ service is usually cheaper to transmit than a DAB service. Therefore, we expect that services may adopt DAB+ where minimising carriage costs is a priority, or where a presence on the broadcast platform is more important than ubiquitous reception (while almost all DAB car systems can receive DAB+, this is not yet the case with domestic sets).

2.22 The concept of small scale DAB relies on the use of relatively low power transmitters for several reasons. These include maximising the re-use opportunity of scarce frequency resources, minimising the risk of receiver blocking (ACI), and keeping the capital and operating costs at modest levels. While these place constraints on the transmitter power levels that might be used for small scale, the newer DAB+ codec can help to improve reception quality and reliability while at the same time avoiding an increase in outgoing interference. This is because DAB+ has a lower signal-to-noise requirement than services encoded with the Layer 2 codec.

2.23 Most DAB+ capable receivers contain the most recent generation of silicon receiver technology. These integrated circuits and modules generally provide much better sensitivity than their predecessors. These receivers can provide a markedly better end-user experience as a result. The digital tick mark[5] helps consumers to select a radio which can receive new DAB+ services and which achieves a minimum level of sensitivity.

[5] http://www.getdigitalradio.com/industry/what-is-the-tick-mark/

Section 3

Ensemble multiplexing

Overview

3.1 The multiplexer is the heart of any DAB transmission platform. It accepts data from multiple sources (local and remote streams or files) and combines them into an output known as the Ensemble Transport Interface (ETI). This is the standardised format accepted by first-generation commercial DAB modulators. The ETI stream was originally presented on the G.703/4 interface once common in carrier grade telecommunications equipment. DAB multiplexers and transmitting plant included the interface as it was the logical technology to use at the time when DAB was developed. This interface has since been replaced with a more modern approach of ETI encapsulated in IP packets which enables use of the now ubiquitous Ethernet interface – this is known as the Ensemble Distribution Interface (EDI). Multiplexers can accept a mixed payload of audio encoded in either of the standardised DAB or DAB+ formats, as well as other data and signalling for advanced features and other applications.

3.2 The original 2012/2013 Brighton test used crc-dabmux, an ensemble multiplexer which was created by the federally-funded Communications Research Centre of Canada[6]. CRC opened the source of the suite under the General Public Licence shortly before ceasing development entirely. The code was subsequently adopted and is being further developed by Open Digital Radio, which has a collective of users and contributors in a number of countries.

3.3 The evolution of crc-dabmux into ODR-DabMux has seen the application evolve from a lab demonstration tool into a ‘production ready’ DAB head-end which is now in full time use in a number of countries. It accepts text files for configuration, uses robust zeromq streams for both input and outputs, handles time-stamping for SFN functionality, and supports a number of implemented information groups which provide additional signalling for applications such as traffic announcements. The application release is v1.1 at the time of writing. The version numbering reflects that the application has now reached a milestone in functionality and stability.

3.4 During the course of the UK small scale DAB trials, the software (when correctly configured) has proved to be robust even in challenging network conditions. Almost all programme feeds in the trials are delivered across public Internet connections, yet provided acceptable performance even in the absence of a standby connection. Higher resilience could be easily achieved by duplicating the encoders, or more simply with a failover or active redundant connection. Fixed Wireless Access operating in the 5 GHz WiFi band has also been used, and appeared to work well for providing connectivity to some multiplexers. One exception was where a 5 GHz link end-point was located close to an establishment which tests marine radar systems in the same spectrum segment.

3.5 Although the multiplexer application itself is ‘lean’, and contains no integrated monitoring functionality, it offers interfaces to common statistical analysis tools, such as Munin graphs, which enables comprehensive monitoring and fault reporting. The

[6] http://www.crc.gc.ca/eic/site/069.nsf/eng/home

addition of the Ensemble Distribution Interface provides interoperability with the latest generation of commercial DAB modulators.

3.6 The ODR-DabMux application is compliant with ETSI standard EN 300 401[7] but not all features in the specification have been implemented at this time. Nonetheless, it has proven to be more than adequate for broadcasters who wish to gain a foothold on the digital radio platform with minimal outlay, and for those wanting a basic yet functional solution that requires little maintenance or user intervention.

3.7 The primary current limitation of ODR-DabMux is that only certain parameters like service labels can be changed dynamically. Major configuration changes (such as the removal or addition of a service) require the multiplexer application to be restarted. This causes a momentary disruption to all services carried in the ensemble. It is therefore good practice to only apply such changes during planned maintenance windows.

3.8 The original crc-dabmux application only accepted configuration through complex command line arguments issued at run time or via a script. It has since been enhanced to support configuration files. This enables configuration templates to be prepared and checked for correctness on a separate staging system before being placed into the production environment. The configuration file contains the global ensemble parameters (EId, SIds, labels, transmission mode flag, SFN time-stamping) as well as the service parameters and output formats.

Issues

3.9 The ODR-DabMux multiplexer has proven to be reliable and dependable, but some industry stakeholders who carried out their own analysis of the multiplex structure expressed some concerns. The first issue related to the toggling of the time confidence indicator, which was an intentional feature introduced as a means of identifying where the ODR software was in use (watermarking). This feature was deemed to be undesirable, and non-compliant with EN 300 401, and was quickly rectified.

3.10 The same stakeholder also suggested that the repetition rates of certain data groups were low when compared to other multiplexes, and that this was non-compliant. However, the ETSI specification only makes recommendations about the repetition rates and does not define hard limits. A large sample of common DAB receivers was tested before bringing the platform into use to help ensure that there would be no negative impact to existing receivers. This was a sensible precaution as receiver technology providers do not share information about how their devices work due to commercial confidentiality concerns. During the trial the Fast Information Channel (FIC) carousel code was replaced by the Open Digital Radio lead developer Matthias P Brandli. This resulted in repetition rates of the Fast Information groups being increased.

3.11 Another stakeholder expressed concern about identical labels being used for both service definition and components. While this was not thought to be an issue for receivers complying with the standards, the duplication was due to a problem with parsing configuration files present in the version of ODR-DabMux which was used for the trials. This was subsequently patched so the duplicate component label could be removed if the operator wished to do so.

[7] http://www.etsi.org/deliver/etsi_en/300400_300499/300401/01.04.01_60/en_300401v010401p.pdf

3.12 The open source code is available to be scrutinised by any interested party. This enables both constructive feedback and code contributions for enhancements and fixes. The stakeholder observations and feedback that we received have been most useful in ensuring that the multiplexer is compliant with the relevant ETSI standards.

3.13 Since the trials were announced we have become aware that several companies have begun to tailor products specifically for smaller scale DAB applications. These include content severs, multiplexing software and 'one box' solutions.

Trial developments: Hardware

3.14 Following on from a previous experiment which demonstrated that a single core ARMv6 processor operating at 700 MHz could 'just about' run the multiplexer, it was clear that commodity System-on-Chip units could offer a compact, low-maintenance, low-cost and low-power solution. More powerful mini desktop computers could also provide a 'one box solution' for certain applications. The Odroid U3 development single board computer (SBC) was initially selected for the trials, and the multiplexer application was compiled on the Ubuntu GNU/Linux computer operating system. This proved to be a good combination.

3.15 The $65 Odroid U3 SBC was demonstrated to stakeholders, and endurance tests demonstrated that it was suitable for use in the trials. However, it was decided that an Intel Core i5 NUC PC would be used instead, as this solution afforded more flexibility in terms of tasks which could be consolidated into a single box, and it also provided more 'headroom' for future developments. Another consideration was that spares or replacement equipment would be much easier to obtain quickly if needed.

3.16 A potential alternative tested during the original test was to host the multiplexing application on a Virtual Private Server, or cloud. This provides the advantage of high bandwidth, good peering of networks, maintained power, environmental conditioning and fault tolerance. The disadvantages are not being in control of maintenance windows or having any direct relationship with intermediate networks. While cloud multiplexing worked well in testing it was considered risky for deployment during the trials because a fault or failure would affect all of the services in the ensemble.

3.17 A few services participating in the trial are however using encoders which run in the cloud. A cloud encoder typically connects to a high bitrate internet stream which is then transcoded to a DAB or DAB+ compatible format and sent onwards to the multiplexer. This is a quick and simple solution but should normally be avoided if possible, as passing the audio through different audio compression codecs can produce unpleasant audible artefacts.

3.18 The trial ensemble multiplexers were manufactured with a generic 'template' configuration consisting of six services at 192 kb/s stereo at UEP level 3. This equates to 840 capacity units out of the 864 available. Initially, changes to the configuration files needed to be carried out manually in a text editor, but some trial operators have added their own Graphical User Interface (in the form of a web interface) to make managing the multiplex possible by non-technical personnel.

Section 4

Modulation

Modulator

4.1 The final software application in the transmission chain is ODR-DabMod. This is a modulator compliant to EN 300 401 which reads the ETI generated by ODR-DabMux, and outputs the digital domain representation of the RF COFDM signal as complex I/Q samples. The application is capable of producing an output signal with higher resolution than is described in the ETSI standard.

4.2 The application is flexible and has been tested with several different radio hardware platforms. Configuration is carried out in a similar way to the multiplexer in that it can read a file which contains the operating parameters. ODR-DabMod is able to decode timestamps inside the ETI, which is necessary if it is to be used in SFN mode. ODR-DabMod supports time-stamp decoding and transmitter offset delays for this purpose.

4.3 The application release is currently at version 0.6 and it is anticipated that it will reach the version 1.0 milestone once Transmitter Identification Information functionality has been completely implemented (TII is a method of identifying individual transmitters in an SFN group to specially-equipped receivers). However, the current version is suitable for production use in standalone transmitters, multi-frequency networks, or single frequency networks that contain two transmitters. This is because with only two different channel impulses, it is simple (in most cases) to determine which transmitter the impulses are from. The modulator has proven to be very reliable in service in several countries. One issue affecting SFN launch delay timing was identified during the UK trials which appears to have been rectified as a result of some refactoring of the source code.

4.4 ODR-DabMod supports a standard ETI input for use in direct conjunction with ODR-DabMux. For deployments where the multiplexer and modulator are in different physical locations the ETI stream is encapsulated in a ZeroMQ distributed computing protocol. This has proven to be reliable for receiving the ETI stream via the public internet.

4.5 A baseband filter is followed by an optional re-sampler and a universal hardware driver for a range of popular software defined radio peripherals. Several other radio hardware platforms have been validated to work with the modulator. These can be used with a UNIX standard output by using a Linux pipe to pass the complex 32-bit IQ samples (or the lower-resolution 8-bit signed samples as defined in ETSI EN 300 401) to the appropriate middleware.

4.6 The COFDM samples require a digital-to-analogue conversion, and the resulting signal needs to be converted to the transmission frequency. This process was carried out by a Universal Software Radio Peripheral which is capable of operating in spectrum between 70 MHz and 6 GHz. The USRP produced a low-level signal which then was used as the drive for a linear power amplifier.

4.7 The completed systems were subject to pre-commissioning tests defined in ETSI EN 301 489-11 and in the Ofcom Digital Technical Code. The tests were conducted in conjunction with the power amplifier feeding an external bandpass filter with a suitable response characteristic. The RF energy was then dissipated by a 50 ohm radio frequency dummy load which had a power handling capability of 1 kW.

Section 5

Amplification

Overview

5.1 The RF power amplifier of a DAB transmitter must be a purpose-designed unit certified to comply with (amongst other things) electromagnetic compatibility regulations and the UK Interface Requirements[8]. This limits the choice of unit to those offered by companies who manufacture and test products specifically for DAB transmission applications. Market testing of amplifiers in the 100-300W RMS output power range revealed a notably large variation of prices.

5.2 The amplifiers selected for the trials were units of sound design offering the lowest 'price per watt'. These units are certified and carry the appropriate 'CE' marking which is required for products placed on the market within Europe.

5.3 Two units from different manufacturers were selected for the trials in order to avoid potential batch problems, and to test that different amplifiers produced consistent performance. Both amplifiers are class AB linear designs and produce a fair amount of waste heat due to the low efficiency of the topology. This inefficiency is of little concern at the relatively low RF power levels required for the small scale concept. The two units selected were capable of 100 to 150 watts RMS power, and each unit cost less than £3,000 (excluding VAT).

5.4 Because the open source modulator solution does not support pre-correction at this time, it is not yet practical to use a more efficient amplifier topology. At higher power levels many amplifiers now employ the classical Doherty technique to improve efficiency.

5.5 Some faults were experienced with both amplifier types: two units had a reliability issue with the front panel metering, while the others contained RF power devices which were later identified to be from a bad batch. These problems were identified during functional and soak testing. Both suppliers were able to resolve the issues quickly.

5.6 All of the trials operate single-ended transmission systems. These have no built-in fault tolerance as there is only one unit of each element in the chain, and this includes the amplifier. All of the systems were supported from a central set of spares held at the Ofcom Radio Station at Baldock in Hertfordshire. When amplifiers failed during the trial they were promptly replaced with a spare. The suspected defective units were then repaired or replaced by the manufacturer.

5.7 The RF power amplifiers have been operating reliably since the initial teething problems. The considerable 'burn-in' that has elapsed since suggests that they should continue to operate reliably during the trial extension.

[8] http://stakeholders.ofcom.org.uk/spectrum/technical/interface-requirements/

Section 6

Filtering

Overview

6.1 Bandpass filters are used to shape the spectral output of DAB transmitters in order to meet the stringent emission masks which protect services in the adjacent spectrum. These filters are relatively large and mechanically complex devices.

6.2 ITU-R BS.1660 defines three separate masks for different use cases, but only the critical mask is currently approved for use in the UK. The BS.1660 critical mask is intended to protect services in adjacent bands. Other countries may require the use of the BS.1660 super-critical mask for special cases where block 12D is used in specific areas, and the non-critical mask may to be used in other cases.

6.3 We considered whether mask filters might be necessary at all for very low power small scale applications, particularly if the modulator could adaptively monitor and compensate for non-linearity and unwanted spurious products. We quickly concluded that this was not currently practical for most use cases, and that filters would be required for the trial transmitters.

6.4 In some cases, backing-off amplifier power can result in a less stringent or complex filtering requirement. However, linear amplifiers deliver their maximum efficiency when they are operated as close to their maximum power output rating as possible. This is due to the standing current needed for the semiconductors to operate in their linear region.

6.5 Some suitable models of bandpass filter are now less costly than they once were, and fitting them habitually is good engineering practice – particularly if the station is installed in close proximity to other radio transmitters.

6.6 A filter rated at 250 watts RMS now costs around £1,000 which is not excessive considering the expected lifespan of the transmitter plant. It is also a safeguard against spurious emissions, and most transmitters (including commercial ones) would not be able to meet the ETSI specifications detailed in EN 301 489-11 without an external filter. Conformity is often achieved by describing the response characteristic of a (required) external filter.

6.7 The filters used in the trial were a frequency-agile component which needed to be ordered pre-tuned to the appropriate transmission frequencies for their eventual deployment. Market testing identified several potential suppliers, but only one offered a tuneable filter in the short lead-time needed. As frequency planning could not be carried out before sites were known, a few filters needed to be re-tuned prior to issue to triallists. The process requires a real-time Vector Network Analyser so this was carried out by an external contractor. The need to re-tune some filters showed that it is advantageous to use a frequency agile filter. However, this may be less of an issue where transmission frequencies are known and are essentially fixed from the outset of a deployment (e.g. in any future wider roll-out of small scale DAB).

6.8 Ofcom may explore the potential for the use of the non-critical mask (or some other form of mask relaxation) for low-power applications which may enable less complex filters and/or circulators to be used.

6.9 It is still feasible that very low-power DAB transmitters could be made to comply with the emission requirements without using mask filters. This could be useful for other applications that might eventually use the technology. These could include MFN and SFN gap filling transmitters, or as a potential digital equivalent of long term Restricted Service Licences (LT-RSLs). These latter services currently use powers below 1 watt in the Medium Frequency band (or 50 milliwatts in the case of FM in certain areas) to serve specific establishments. These include university campuses, hospitals and schools. These potential applications have not been considered in detail as they are outside the scope of this project

Section 7

Contribution and distribution

Overview

7.1 Several different types of IP broadband circuits were used by the trials for the connectivity between encoders and ensemble multiplexers, and between multiplexers and distant transmitter sites (when needed to form an SFN). The circuits needed to provide sufficient aggregate throughput to transport the encapsulated ETI feed without interruption. This can be achieved by tuning buffers to store enough data to overcome the longest period of network stalling or contention observed during the testing phase.

7.2 Broadband contention ratios need to be low in order to prevent network loading by other users from causing interruptions. During the trials, low-cost business grade DSL circuits (without data transfer caps) were found to provide adequate performance for the stream ingress from multiple encoder sources. However, these circuits were not suitable for delivering the multiplexed ETI feeds to remotely located transmitters due to the inherent asymmetry between upload and download transfer rates.

7.3 For SFN operation in particular, circuits must offer predictable throughput with low error rates. Low cost 5.8 GHz Ethernet bridges and Ethernet over Fibre To The Cabinet (EoFTTC) have both been tested successfully for supporting SFNs.

7.4 A backup wireless bridge sustained a two-transmitter SFN during a prolonged circuit outage. The fault was severe enough for it to persist for six days beyond the contractual service level agreement which illustrates the importance of providing diverse connectivity paths to the ensemble multiplexer – a mix of bearer technology and service providers may reduce the risk of core and access network faults which may affect all connectivity paths provided by a single supplier.

7.5 For SFN applications in particular, EoFTTC and Ethernet First Mile (EFM) are currently available for point-to-point and any-to-any connectivity in around 90% of exchange areas. These products offer suitable performance, resilience, and a six-hour fault resolution in most circumstances. Such circuits should take around 25 working days from order to provision, but it was found in some cases that this took considerably longer in practice. The cost of EFM and EoFTTC is several times higher than the more common ADSL and VDSL services.

7.6 For non-SFN operation, the multiplexer may be co-located with the transmitter and the programme feeds can be delivered via any means considered practical, although off-air feeding should be considered the last resort due to the loss of quality and because of security concerns.

Section 8

Aerials and feeders

8.1 Aerials are generally ordered for the frequency of interest and cut to length during the manufacturing process. During procurement we identified a company that could deliver within the short lead time we needed in order to keep to our very tight launch schedule. The cost was also competitive so these were ordered as soon as the final site details and frequencies for the trials were known.

8.2 As we had neither sufficient time or resources to design a bespoke system for each trial it was decided to standardise on an end-fed co-linear aerial type with 3dBd of gain, as these were small enough to easily transport and erect. The gain made up for the system losses incurred in the mask filter and the feeder cable. The angle of radiation in the vertical plane was also beneficial for minimising blocking (ACI) providing the aerial was mounted at a reasonable height above the surrounding terrain and dwellings.

8.3 6dBd co-linear aerials were delivered to the London trial with the agreement of the operator due to heightened ACI concerns as both sites were in very densely populated areas, and because of the high number of existing multiplex services in the area. This aerial type was also helpful in ameliorating (to some degree) blocking caused by a business radio system with many mobile stations, and 'reverse ACI' from other DAB networks which lay down much higher field strengths (due to the greater number, and higher power levels, of the transmitters in those networks.)

8.4 At a few sites, triallists proposed to use existing mast structures rather than rooftop sites. Existing mast sites were provided with cardioid pattern aerials to largely de-couple the effects of the supporting structure on gain and pattern. A cardioid aerial was also provided for the on-channel repeater site. These aerials were later replaced as they were found not to provide the claimed high front-to-back ratio, or the horizontal radiation pattern expected.

8.5 The feeder cable selected for the trials was of a coaxial type with a rated loss of circa 6dB per 100m at 200 MHz. The seven-strand inner conductor, polyurethane dielectric, and copper braid screen made it more attractive than the lower loss solid conductor cables with a PVC coated corrugated copper screen as the latter are more susceptible to damage from crushing and bending. The higher loss of the cheaper, more durable cable was therefore considered to be acceptable.

8.6 One operator installed their own cable instead of the one supplied. This was discovered on commissioning due the connectors being a noticeably poor fit. The cable used, RG214, has a considerably higher loss of ~11dB/100m at the frequencies of interest. The cable braid also caused a short circuit at the output of the mask filter as the connectors were not the correct parts for the cable used. No damage was caused, but the system losses were much higher, particularly as the cable run was quite long.

8.7 Another operator installed a gas discharge lightning arrestor in the feeder cable at the request of the site landlord. The site failed commissioning due to poor spectral purity, and the arrestor was eventually found to be the cause of the problem. It is thought that the high crest factor of the DAB signal was causing electrical breakdown in the arrestor due to the peak voltages approaching or exceeding the striking voltage.

8.8 Two trial transmitters were installed in buildings also containing communal aerial distribution amplifiers. The DAB transmitters were found to cause problems to domestic digital terrestrial television (DTT) reception. Many domestic aerial amplifiers have a very wideband response, and operate at VHF frequencies in addition to the UHF band used for TV. The proximity of the DAB transmitting aerials caused these amplifiers to be overloaded.

8.9 The commissioning process was suspended while bandpass channel filters were fitted to the input of each aerial distribution amplifier. This resolved the problem in both cases. Interference to domestic reception did not occur at other trial transmitter sites.

Section 9

Commissioning

9.1 The small scale trial multiplexes were subjected to the same commissioning checks which are carried out for all DAB transmitters in the UK. These included pre-compliance checks by the operator of the service for and health and safety issues, including prevention of public exposure to excessive levels of non-ionising radiation. Once installed and fully prepared by the trial operator, Ofcom engineers then carried out drive surveys of existing DAB multiplex signal levels in the vicinity of the transmitter. We then visited the transmitter site to carry out a full commissioning of the system into antenna, and carried out a further coverage survey of existing DAB multiplexes to ensure that their coverage was not impacted by ACI caused by the trial transmitter.

9.2 The on-site commissioning process consists of measuring the operating frequency, power and spectral occupancy (including spurious and harmonic emissions) to ensure they are within the tolerances set out in Ofcom's Digital Technical Code[9]. We also check the aerial installation for compliance with the Code and that the agreed mounting position has been used.

9.3 As the trial multiplexes began to launch, Ofcom formed three different commissioning teams to spread the workload. Whilst most services were commissioned without any issues there we a few instances where remedial work was needed before the transmitting station could be brought into service. One notable instance where further work was required was where building work had commenced shortly after installation of the antenna system. The builders erected scaffolding in very close proximity to the transmitting antenna, resulting in a possible infringement of the ICNIRP regulations and presenting a possible RF safety hazard to building workers. Transmissions were ceased until the aerial could be repositioned and re-tested.

[9] http://stakeholders.ofcom.org.uk/binaries/broadcast/guidance/tech-guidance/digi_tech_code.pdf

Section 10

Coverage and adjacent channel interference

Coverage

10.1 We set the trial operators a challenging, but achievable, timeframe to launch of twelve weeks from the offer of a trial licence. This was necessary to ensure the multiplexes were broadcasting for a reasonable amount of time during the period in which project funding was available.

10.2 This, coupled with the temporary nature of the trial, was not conducive to operators securing the best transmission site in many cases. For example, it can often take considerable time to negotiate access and then secure agreements with site landlords. It was therefore expected that most operators would utilise sites for which they already had an agreement to use, or ones that could be quickly secured for the duration of the trial at minimal cost.

10.3 One operator informed us that they deliberately used a site that they owned, and that they were aware its coverage would be relatively poor. However, they considered that the technical aims of the trial could be met even when a sub-optimal site was used.

10.4 Another triallist moved to a better-suited site part of the way through the initial trial period. The opportunity to study this site move provided valuable insight into how operators might move a ‘live’ site. Other operators have subsequently submitted various proposals to change or add transmitter sites. These were considered on a case-by-case basis for their novelty, and if we could learn anything useful from the proposal, with a general constraint that a site move should not cause the coverage area of the multiplex to be extended beyond that which was originally achieved and/or applied for.

10.5 None of the operators chose to employ higher levels of error protection in order to optimise coverage. Presumably either this was because the coverage was satisfactory, or because of the cost to capacity resources. All services on the trials currently employ UEP3 for DAB or EEP-3A for DAB+. The latter generally appears to have been used to fit a greater number of services into the multiplex rather than for enhancing coverage or improving sound quality.

10.6 DAB+ at EEP-1A could reduce the signal-to-noise requirement by up to circa 4.5dB when compared with DAB at UEP3. This would provide a significant gain for multiplexes seeking to improve reception robustness or coverage, and (unlike a power increase) does not increase outgoing interference or the risk of ACI.

10.7 Receiver performance can also significantly affect the perception of coverage. We tested a sample of receivers and found a very significant variation in sensitivity. We later contracted the DTG to carry out independent tests. The DTG report (Annex 6) correlated closely with our findings. There was a circa 20dB difference in sensitivity between the best and worst receivers in our sample. Most newer sets which support DAB+ use the latest generation of receiver technology, and are also more likely to carry the ‘digital tick mark’ which requires sets to meet or exceed a minimum sensitivity level.

Adjacent Channel Interference (ACI)

10.8 When a licensee wishes to bring a new DAB transmitter site into operation Ofcom considers whether and to what extent this might lead to ‘hole punching’ in the coverage of other multiplexes on adjacent-channel frequencies which serve the same area.

10.9 When considering the impact of ACI for the small scale DAB multiplex trials, we adopted the same process as used for existing DAB multiplexes. The principles for the management of ACI are set out in the ‘Ofcom Technical policy guidance for DAB multiplex licensees’[10] document.

10.10 Ofcom engaged with the relevant licensees once the transmission parameters for the trial sites were finalised and an initial prediction was run in order to gauge the likely levels of interference. Ofcom also met with the BBC and Arqiva spectrum planners to form an initial view of the shortlisted sites. These assessments were carried out in a manner consistent with that adopted by the JPRG[11] ACI sub-group.

10.11 We expected that transmitters for these trials would operate with an ERP of around 100 watts and generally be on frequency block 9A or 9C, although some exceptions assumed operation on block 10B or 10D. The use of frequency blocks not currently occupied by DAB reduces the potential for ACI to occur. Our initial assessment was that some of the proposed SS DAB sites presented a very low risk of causing ACI, while others were thought to likely require some mitigation.

10.12 Given the limited trial duration, it was not proportionate to consider the implementation of filler transmitters. We therefore proposed to attend the commissioning of all of the trial SS DAB sites and measure the coverage of existing services within 500 metres of the installation prior to and after commissioning. This was necessary to gauge the magnitude of any interference or blocking.

10.13 We intended to mitigate any significant impact through measures such as modifying antenna arrangements and/or power reductions. Furthermore, all of the small scale DAB trial licences contained a provision through which we could require the transmissions to cease if they caused undue interference to other services.

10.14 In practice, the blocking effect caused by the trial transmitters was far less evident than was predicted by computer modelling, and at worst there was a small reduction of the percentage of locations served in the immediate vicinity of the site.

10.15 We believe the reason for this is because the prediction tool will produce a 'worst case' result because such tools do not have sufficient resolution in their models about the local environment - for example they lack information about buildings or vegetation, which can attenuate radio signals and therefore reduce the local signal levels below what would otherwise be a free space loss calculation.

[10] http://stakeholders.ofcom.org.uk/binaries/broadcast/guidance/tech-guidance/policy_guidance.pdf

[11] The Joint Planning for Radio Group: a group chaired by Ofcom which contains representatives of its digital radio multiplex licensees (and the BBC) which is used to develop Ofcom’s policies on digital radio spectrum management.

10.16 The protection ratios used to date for predicting ACI were established when lower resolution (8-bit) analogue to digital converters were used in receiver baseband processors. More recent receivers are thought to use higher resolution converters which enable them to process signals with a higher level variance, and so are less prone to blocking.

10.17 Generally, where the signal from other multiplexes was of a usable strength, no significant levels of blocking or ACI were detected, although one member of the public located approximately 100 metres from a trial transmitter reported the loss of reception of one multiplex. This problem was resolved when the listener repositioned the receiver.

10.18 At some trial sites, industry stakeholders carried out their own ACI measurement exercises in addition to the ones carried out by Ofcom. The findings by all parties were that there seemed to be very little correlation between audible errors and measured BER, with failures only noted where the signal strength of the trial transmitter was around 55dB above the wanted signal. While outside the scope of this project, this significant difference could provide an opportunity to re-assess the current methodology for predicting ACI, as these results indicate that a simpler approach could provide adequate protection for listeners. Remedies other than building filler transmitters also exist and could be considered.

Section 11

Lessons: Single transmitter trials

Overview

11.1 The single transmitter trial equipment was housed in a 12RU flight case for ease of integration and transportation. Although the active equipment only occupied 7RU, the larger case ensured there was adequate airflow, and an extra shelf provided a place for mounting the connectivity provider's network termination and routing equipment.

11.2 The case contained a VLAN-aware managed network switch, a Core i5 NUC (a mini PC), B200 software defined radio and a VHF linear amplifier. A small line interactive UPS was also fitted to condition the mains supply for all components of the system apart from the amplifier. The UPS was also intended to provide isolation from the mains supply in case of commutation spikes and transients caused by nearby lightning strikes or other equipment which might be present on the same supply phase.

11.3 The NUC PC ran the Debian 8 GNU/Linux distribution which had been customised through configuration and the addition of the necessary software components. A set of configuration templates enabled the completed systems to be tested in a straight-forward and repeatable manner, and to enable them to be ready to operate into a radio frequency dummy load immediately after the final assembly had been completed.

11.4 In the standalone configuration, the ensemble multiplexer (ODR-DabMux) was configured to send the ETI stream directly to the modulator (ODR-DabMod) application using standard outputs and inputs. Linux pipes enable this data to be passed between the two applications directly.

11.5 The design ethos was to provide a 'bare-bones' system which was relatively easy to understand, and we provided each trial operator with a single one-to-one training session on the use of the system. These training sessions lasted between two and four hours (depending upon technical ability) and this seems to have been sufficient. Initial configuration files were created and tested in the presence of each operator. The approach encouraged and enabled operators to learn about their transmission system, and the system's initial simplicity encouraged some operators to add their own monitoring and control systems.

11.6 The type 1 (single transmitter) trial operators appear to have had very few problems during the initial trial period, and the platform has proven to be very reliable in service. Most of the trials have not needed to do much more than make changes to the multiplex configuration when required (e.g. to add new audio services to the multiplex).

11.7 Although the transmitter equipment racks were designed to operate for the initial 9 month trial period, it is expected that they will continue to operate into the extension period providing the environment in which they are installed is clean and has adequate airflow to dissipate the exhaust heat from the amplifier.

Figure A2: two of the 12RU trial racks undergoing functional testing

Section 12

Lessons: Single Frequency Network trials

Overview

12.1 Single Frequency Network (SFN) operation required considerable additional attention compared to the 'set and forget' nature of the single transmitter trial systems. The software patches to enable SFN operation had not been used in production previously, so additional work was needed to identify and validate suitable hardware combinations and software configurations.

12.2 An ongoing test of running the ensemble multiplexer in a cloud service indicated that full duplication with separate infrastructures and connectivity would be required to prevent extended unplanned outages. It was also considered that such a solution would place too much reliance on third parties and make it difficult to identify the location and cause of connectivity issues. Relying on third party infrastructure can also potentially increase susceptibility to direct or indirect Denial of Service attacks.

12.3 Therefore, it was decided that the multiplexer should run at a nominated principal, or master, transmitter site and that each slave transmitter site could also take on the multiplexing role if needed.

12.4 One of the SFN trials connected their sites to the Internet via an EoFTTC service, and also cross-connected them with a fixed microwave link to provide resilience against circuit failure. This approach also extended the LAN to both sites. This additional link proved to be very useful for fault investigation and resolution. Each of the two sites could receive streams from the source encoders, even though most of these streams were configured to just send to a single destination. Either site could additionally be used as an ingress route to pull alternative sources such as web streams in case of temporary failure in the primary feed.

12.5 The other SFN trial encountered difficulty in provisioning suitable connectivity for supporting SFN operation. An attempt to connect a transmitter to the public internet via a domestic cable internet service which was extended onwards to the site by WiFi seemed to work in single transmitter mode, but the stability of the SFN operation has not been satisfactory. Both SFN trials were provided with identical software and hardware, with the exception of the power amplifiers as these were provided by two different suppliers.

12.6 The transmission racks were identical to those used by single transmitter trials with the exception of an additional timing module fitted inside the SDR and a slightly different version of the modulator and Universal Hardware Driver software. The module also required a Global Positioning System aerial to be installed on each site, as the timing modules utilise GPS to discipline the reference oscillators such that they have long-term sympathy with all other transmitters in the group.

12.7 Originally, GPS modules were procured from the same supplier as the radio unit, but maintaining synchronisation using these modules was initially found to be problematic. Due to project timescales an alternative solution was sought. We therefore used alternative GPS modules based on a commercial RF module. These needed to be hand-soldered to an open source daughterboard specifically designed by the Open Digital Radio group to enable it to be interfaced to the radio unit. Debugging of the SFN timing has been an on-going process, and the problem with the original ‘stock’ timing modules was subsequently found to be due to a software issue, and was resolved.

12.8 The alternative module performed well during an issue affecting the GPS satellite constellation. The decommissioning of GPS satellite SVN23 on 26 January 2016 caused problems with the synchronisation of some DAB transmitters. The operational small-scale SFN trial was not affected – possibly because the timing devices can utilise signals from other Global Navigation Satellite Systems in addition to GPS.

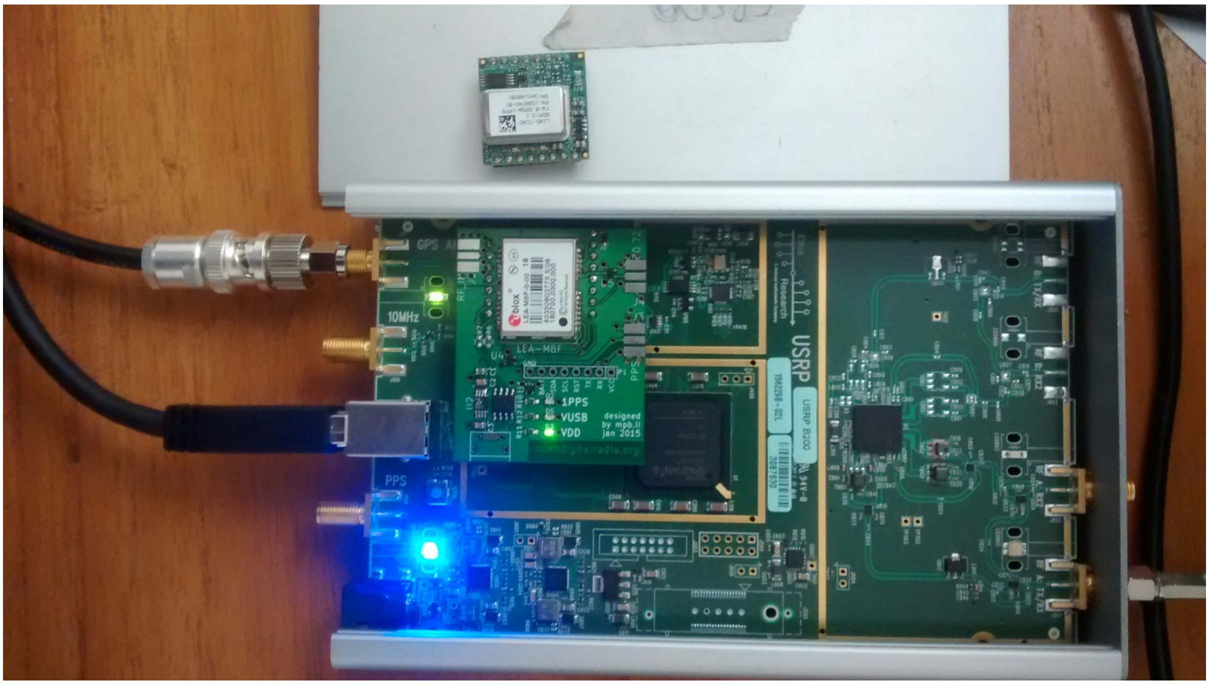

Figure A3: Software defined radio board with timing modules

12.9 The most significant issue with SFN operation during the trials was a lack of long term synchronisation stability. Although the RF carrier frequency was tightly controlled by the GPS-disciplined oscillator references, the RF launch delay time appeared to change suddenly by around 400µs after (on average) six days of continuously synchronous operation. This could be prevented through a pre-emptive reset of the modulators during maintenance windows.

12.10 This difference in the launch time of the transmitted data is almost double the time difference which DAB Transmission Mode 1 is designed to withstand. This resulted in a loss of network gain, and destructive inter-symbol interference in a ‘mush zone’ where the transmitter coverages overlapped. The loss of correct synchronisation therefore led to periodic reception problems within this area.

12.11 The investigation work around this timing issue has taken a considerable amount of effort. However, we now believe that the problem has been resolved after significant refactoring of source code by Open Digital Radio. A new build of the platform for SFN will be released by Ofcom to the two SFN trials during September 2016.

12.12 One potential issue related to SFN operation of small-scale multiplexes is that the capital and operating costs are broadly proportional to the number of transmitters within the SFN. As discussed earlier, higher grade (and higher cost) circuits may also be required for new transmitters in an SFN, which would further increase costs.

Section 13

Lessons: On-channel repeater trial

About on-channel repeaters

13.1 Practical on-channel repeaters (OCRs) for DAB were first described in a BBC Research & Development paper[12] from September 2005. Such devices can be used in conjunction with a main transmitter to form a (largely overlooked) type of Single Frequency Network. They can extend coverage in the same way as a regular SFN transmitter site, but do so by receiving and transmitting on the same frequency.

13.2 OCRs do not require distribution telecoms circuits. So although the initial equipment costs are higher than for more conventional network architectures, they can potentially deliver significant cost savings over the life of the plant. They can also be used in locations where providing connectivity might be problematic or prohibitively expensive.

13.3 OCRs require a strong, reliable incoming ‘donor’ signal, as well as considerable RF isolation between the receiving and transmitting aerials at the OCR site. Local echoes caused by reflections from nearby buildings and terrain are removed from the signal during conditioning, which is carried out by dedicated digital signal processing circuits. The process is adaptive and can deal with environmental changes which may cause the echo characteristics to change.

13.4 The need to achieve quite high levels of isolation between the receiver and transmitter in the repeater unit does place constraints on where such an installation is practical. GPS disciplined oscillators are not required as the donor transmitter provides an adequate reference.

Initial investigations

13.5 As there is very little literature available about how these units actually perform in service, we decided to carry out practical trials of the OCR concept as part of the small scale DAB trials.

13.6 Ofcom engineers obtained a sample of the only complete and commercially available OCR unit found during market testing. This was evaluated during the project preparation phase at Baldock Radio Station in Hertfordshire. A DAB test transmitter comprising of an Odroid U3 module and a B100 software defined radio was established inside a cabin on an enclosed area of the estate. This fed a low power amplifier and mask filter and radiated from an end-fed dipole aerial mounted on a telescopic trailer-mounted mast. The arrangement provided 1 watt ERP on block 11A and this provided the donor signal for the OCR.

13.7 The OCR was installed in another compound around 0.5 km away. The OCR site had approximately 50m of separation between a cardioid transmitting aerial and a seven element yagi aerial (used for receiving the signal from the donor transmitter). The separation distance need not be so great if physical obstructions can be used to provide attenuation of stray radiation in the path between the two aerials.

[12] http://www.bbc.co.uk/rd/publications/whitepaper120

13.8 The isolation was optimised using a spectrum analyser connected to both aerials, and the transmitting mask filter was left in circuit whilst the aerial positions were optimised. The power received by the donor aerial was then measured. Isolation in excess of 90dB was achieved. A reduction in the high levels of local echoes caused by a chain link fence was achieved by increasing the donor aerial height. The optimisation process enabled the unit to operate at its full rated power output of 100 watts RMS.

13.9 Initial checks for receiver blocking (ACI) were carried out, with particular attention paid to reception of the in-use adjacent DAB block (10D). As reception was not impaired (because the signal from 10D was very strong locally), the transmitter was able to operate for extended periods during which drive test surveys were conducted.

OCR deployment during the trials

13.10 Because of the very encouraging test results, the OCR was selected for further testing at one location during the stakeholder trials. The trial site was a tall church bell tower, which is not an ideal structure as several technical requirements which could not be fully met. The separation distance between the aerials was less than optimal, and the desired 7-element receiving yagi aerial could not be used due to aesthetic and practical concerns. Alternative aerials were sourced, but these were found not to provide the predicted isolation and were later found to have a design defect. Replacement of these did not significantly improve the situation and the transmitter was operated at 50 watts ERP for the remainder of the trial period in order to maintain a sufficiently stable isolation margin.

Possible alternative applications for OCRs

13.11 The OCR architecture may offer the technical potential for other new DAB applications, such as a novel form of studio-to-transmitter distribution architecture (i.e. providing a feed to an operator’s ‘primary’ DAB transmitter site from a studio or multiplexing centre without the need for IP circuits or other data links). In this application, a directional and relatively low-power small scale DAB transmitter could be used at the studio site, with the signal being directed towards the primary transmitter site, where an OCR transmitter could provide the principal coverage for the service.

13.12 The use of opposite slant (or circular) polarisation could deliver some additional isolation if used at the donor transmitter, but such an arrangement could increase the risk of blocking due to the angle of radiation on some bearings.

13.13 The OCR test bed was demonstrated during a stakeholder technical event as a proof of concept, and many attendees recognised the benefit of feeding the ‘best server’ transmitter from a low power source located elsewhere. In this situation, the donor transmitter can also provide local coverage (as the OCR transmit aerial would generally be directed away from the donor transmitter). This is a very spectrally efficient approach by virtue of it using the same frequency block, and it therefore has no spectrum opportunity cost. Further isolation gains are technically possible by alternating the polarisation between the receiver and transmitter. While all current UK DAB services use vertical polarisation, opposite slants or circular polarisation could potentially be employed between master and slave stations.