THE QUEEN'S AWARDS FOR ENTERPRISE 2001

BBC

R&D White Paper

WHP 120

September 2005

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A. Wiewiorka *and* P.N. Moss

Research & Development
BRITISH BROADCASTING CORPORATION

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This document was originally published in the Proceedings of the International Broadcasting Convention, September 2005.

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DIGITAL ON-CHANNEL REPEATER FOR DAB

A. Wiewiorka and P.N. Moss

BBC Research & Development, UK

ABSTRACT

The provision of full coverage to the public can be a difficult task in terrestrial broadcasting. Sometimes, due to technical challenges and cost constraints, it may not be possible to deploy conventional signal distribution to transmitting stations. In these cases an on-channel repeater may be the only viable option. This paper describes a BBC digital on-channel repeater designed to extend the coverage of DAB services, believed to be the first device of this kind tested for broadcasting purposes in the UK. The unit receives a signal from a distant transmitter and re-broadcasts an amplified and slightly delayed version of it on the same frequency. In order to avoid instability caused by parasitic coupling between the receiving and transmitting antennas, stray transmitted signals are cancelled by an adaptive filter with a Least-Mean-Square estimator. The theory of operation is explained and hardware implementation is discussed. Results of a field trial are also presented.

INTRODUCTION

Ensuring maximum possible coverage of terrestrial broadcast services can be technically difficult and expensive. The line-of-sight nature of modern broadcasting imposes the requirement for a large number of transmitters as well as a complicated signal distribution system involving UHF, microwave, satellite, or cable links. Apart from the problems of topography, there may also be issues of co-existence with other operators, who might own or control suitable transmitter sites or the means of signal distribution. In circumstances when traditional solutions for coverage extension cannot be deployed, an on-channel repeater may be the only viable alternative. The BBC first identified the potential need for on-channel repeaters in relation to hole-filling in the coverage of its Digital Audio Broadcasting (DAB) services.

An on-channel repeater retransmits a signal on the same frequency as it receives, so that no frequency translation is required, as is the case in RF or satellite links. However, due to unwanted coupling between the receiving and the transmitting antennas, the device can also receive its own output, thus causing instability and relaxation oscillations. For this reason analogue on-channel repeaters require large antenna isolation and are suitable mainly for point-to-point links rather than broadcast purposes such as DAB.

The device described in this paper employs suitably adapted echo cancellation techniques used extensively in digital signal processing for audio applications. Although these methods have been known for a considerable time, a commercially viable implementation using digital hardware running at the speed required for digital broadcasting only became possible around 2002. The theory of operation is explained in the next section, together with the mathematical basis of the adopted solution. The important aspects of operational use, such as the suitability of a transmitter site are addressed. Both analogue RF and digital design issues and constraints are presented followed by the description of the adopted implementation. Finally the results of a field test are shown and discussed.

THEORY OF OPERATION

An on-channel repeater receives a weak signal through a receiving antenna and reradiates an amplified version of this signal, on the same frequency, using another antenna. Due to the physical proximity between the antennas, as well as reflections off the ground and nearby objects, there may be a significant amount of unwanted feedback from the output of the repeater into its input. If not removed, such feedback causes instability and relaxation oscillations that render the signal unusable.

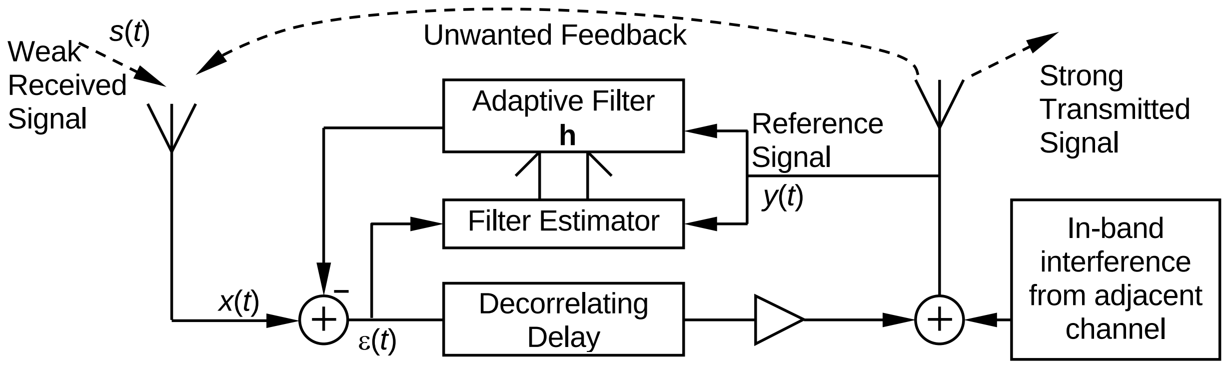

Figure 1 – Simplified block diagram of an on-channel repeater.

The cancellation of parasitic feedback is performed by an adaptive finite impulse response filter which models the path between the antennas. The filter impulse response **h** can be estimated using correlation methods, provided that the delay through the system is sufficiently long to avoid the effects of autocorrelation. In other words, the retransmitted signal, and hence the feedback, must be uncorrelated with the received signal, so that it can be unambiguously identified. In fact, apart from delayed $\varepsilon(t)$, $y(t)$ may contain a number of interfering signals such as intermodulation products from the power amplifier or even intermodulation products from adjacent channels, if present.

The simplest, and in most cases entirely sufficient, method of estimating filter taps is the Least Mean Square (LMS) algorithm. Given the input $x(t)$ and output $y(t)$, the objective is to minimize the error $\varepsilon(t)$, leaving only the received signal $s(t)$. This signal is recovered by subtracting from $x(t)$ the output $y(t)$ filtered by **h**, as shown below:

$$\varepsilon(t) = x(t) - \mathbf{h}^{\mathrm{T}}\mathbf{y}_t \qquad \text{..(1)}$$

Vector $\mathbf{y}_t$ contains $y(t)$, $y(t\text{-}1)$ to $y(t\text{-}K\text{-}1)$ where K is the length of **h**. Ideally all remnants of $y(t)$ are removed from $x(t)$, and the energy in $\varepsilon(t)$ is minimized. In order to achieve this goal the filter taps **h** must be estimated. First the expectation of squared magnitude of $\varepsilon(t)$ is defined

$$\mathrm{E}\,|\,\varepsilon(t)\,|^2 = \mathrm{E}\,|\,x(t) - \mathbf{h}^{\mathrm{T}}\mathbf{y}_t\,|^2 \qquad \text{...(2)}$$

and differentiated with respect to **h**:

$$\frac{d\,\mathrm{E}\,|\,\varepsilon(t)\,|^2}{d\mathbf{h}} = -\mathrm{E}\left\{\mathbf{y}_t\left[x(t) - \mathbf{h}_t^{\mathrm{T}}\mathbf{y}_t\right]^*\right\} = -\mathrm{E}\left[\mathbf{y}_t\,\varepsilon(t)^*\right] \qquad \text{...........(3)}$$

The taps are then updated with an appropriately scaled conjugate of the instantaneous value of the derivative:

$$\mathbf{h}_t = \mathbf{h}_{t-1} + \lambda\varepsilon(t)\mathbf{y}_t^* \qquad \text{..(4)}$$

The value of λ is chosen as a compromise between the speed of convergence and signal-to-noise ratio. In practice, faster convergence allows the algorithm to follow rapid changes in the feedback path caused by Doppler paths and multiple reflections, at the expense of increased noise in the filter tap estimates **h**, which affects feedback cancellation. Similarly, in the case of slow convergence and in the presence of Doppler, $\varepsilon(t)$ may contain a significant remnant of $y(t)$, also causing instability. Because the level of this residual feedback is proportional to the loop gain of ε, the amount of Doppler variability in $x(t)$ imposes an upper limit on the gain of the repeater.

As discussed in Marple (1), convergence also depends on the eigenvalues of the covariance matrix $\mathbf{R}_{yy}$=E($\mathbf{yy}^*$). Optimal behaviour occurs when all eigenvalues are equal, but if $\mathbf{R}_{yy}$ is not full rank, or some eigenvalues are close to zero, convergence is significantly impaired. One of the consequences of poor convergence might be large amounts of noise generated in unused areas near the edges of the Nyquist band. For this reason, the choice of sampling rate has to be carefully addressed and best results are achieved if the input signal is noise-like in nature. In contrast, other algorithms such as Fast Recursive Least Squares estimate the autocorrelation of the recovered signal and have assured convergence properties (1). Implementation of Fast RLS is however considerably more demanding of hardware resources.

THE ON-CHANNEL REPEATER AND THE DAB COVERAGE PROBLEM

The reasons for filling gaps in coverage of a broadcast service can be divided into two broad categories:

Coverage extension: If signal strength is insufficient in a particular area, the repeater can be used as an additional transmitter in the Single Frequency Network (SFN). In this case the repeater must have good input sensitivity. If the area to be covered is large, the required gain could be as high as 100dB.

Hole-filling: Signal strength is sufficient but signals on adjacent channels are so strong that domestic receivers may not have sufficient dynamic range to recover the wanted channel successfully. In extreme cases, in areas very close to adjacent channel transmitters, the intermodulation products from the adjacent channels interfere directly with the wanted signal even though spectral mask requirements have been fulfilled. When used in such an environment, the repeater must exhibit very large dynamic range and very good selectivity. Indeed, the device must remove the intermodulation products of co-sited adjacent channels that arrive at its input together with the unwanted feedback. To do this the use of a common antenna feed is necessary.

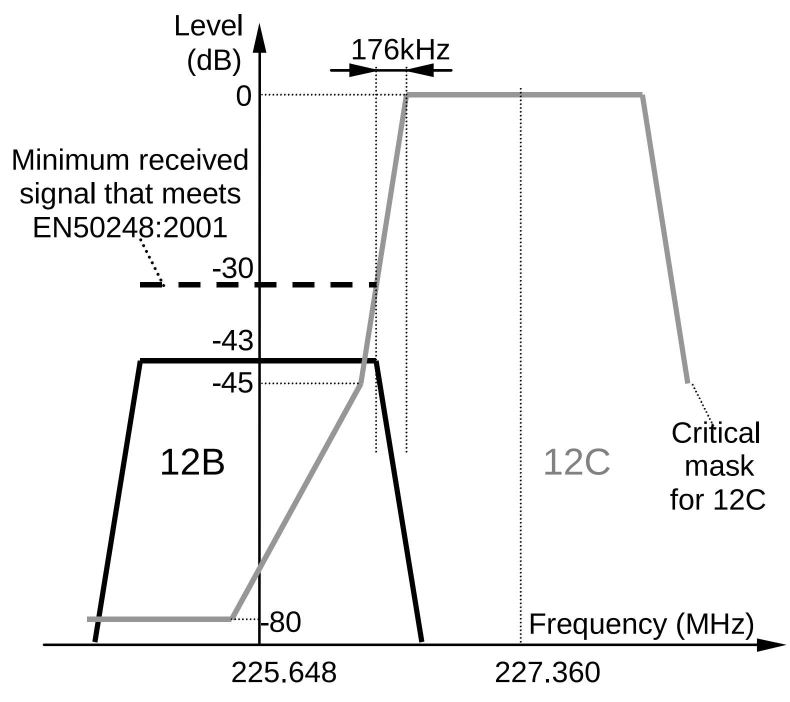

Figure 2 – Reception conditions in the presence of a strong adjacent channel.

Figure 2 shows typical signal levels observed in an area of Nottingham, UK, where the wanted signal on channel 12B is 43dB below the adjacent channel 12C. According to EN50248:2001, Section 7.3.3, a consumer DAB receiver must be able to decode a signal surrounded by adjacent channels at +30dB and cope with any signals 5MHz away from the centre frequency at +40dB. Even before allowing an additional margin of 10dB for fading, it is clear that the signal on 12B is unlikely to be decoded by a typical commercial receiver.

A decision on whether to deploy an on-channel repeater should be based on the measurement of antenna isolation A_A and the minimum received signal strength P_{RX}. Given the target power P_{TX}, the power of intermodulation products P_{IP} from adjacent channels (if any), and the cancellation capability of the repeater A_R, the estimate of "signal to interference" ratio S is:

$$S = A_A + A_R + P_{RX} - 10\log\left(10^{\frac{P_{TX}}{10}} + 10^{\frac{P_{IP}}{10}}\right) \quad \text{(dB)} \quad ....(5)$$

To ensure stability S should not be smaller than 15dB. In the absence of intermodulation this amount of feedback corresponds to approximately 3dB peak-to-peak ripple in frequency response of the system and is seen by a DAB receiver as additional delayed components of the channel response. Large amounts of uncorrelated interference and noise can also be tolerated because DAB uses differential QPSK modulation which produces 10^{-3} bit error rate at 11dB carrier-to-noise ratio.

The statistics of OFDM signals are noise-like and thus ideal for processing with an LMS algorithm. Another advantage is the existence of the guard interval, 246μs in the case of DAB mode I, approximately one fifth of symbol duration. This allows the repeater to introduce a processing delay sufficient both to cancel distant reflections and to decorrelate the feedback signal from the input signal. On the other hand, the delay must be short enough not to disturb the operation of the DAB single frequency network. It is expected that some receivers that do not position their FFT window to include all significant components of the channel response may exhibit problems with time synchronisation.

IMPLEMENTATION

Performance requirements

The repeater was designed for a typical situation shown in Figure 3. At its main input, fed from the receiving antenna, the device should cope with a parasitic feedback to received ratio of 30dB, while the cancellation of this feedback should be at 45 to 50dB in order not to degrade the signal to noise ratio of the recovered signal. If the repeater is co-sited with an adjacent channel transmitter, the preferred solution is to transmit from the same antenna as the adjacent channel. The reference input of the repeater can then be fed with a combined

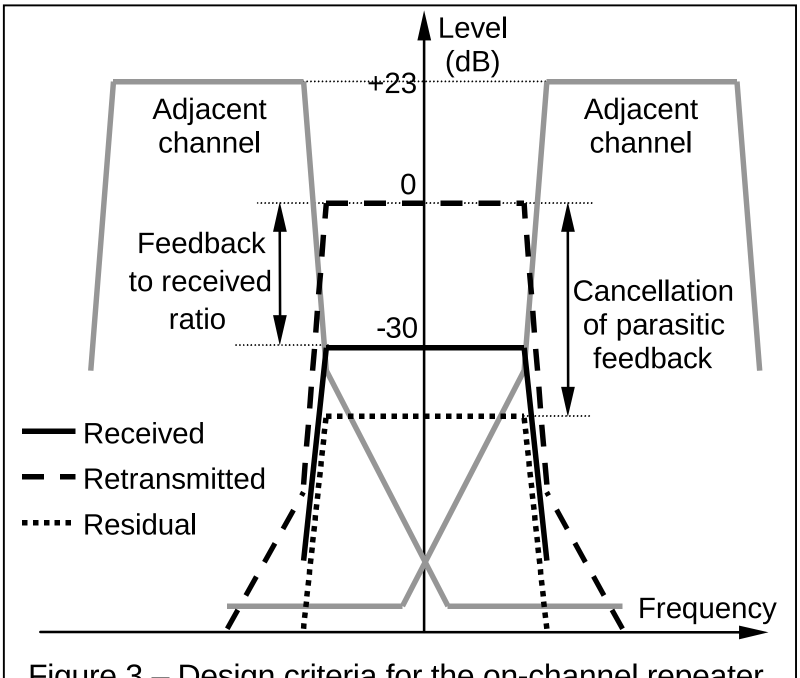

Figure 3 – Design criteria for the on-channel repeater.

signal transmitted through the antenna that contains not only the wanted but also the adjacent channel, so that its intermodulation products can be cancelled as well, avoiding undesirable re-radiation. This is a consequence of the fact that signal *y*(*t*) in Figure 1 need not be related to the recovered signal $\varepsilon(t)$. Indeed those two signals must not be correlated within the time period equal to the length of the adaptive filter. The adjacent channel signals can be up to 53dB larger than the received wanted signal, imposing stringent requirements on selectivity of filters, linearity of mixers and dynamic range of digital-to-analogue converters.

A further constraint affecting the design of the digital filters is the requirement to keep the processing delay as short as possible, preferably below 20μs, i.e. less than one tenth of the guard interval.

Circuit description

The prototype on-channel repeater is implemented as a single hardware unit with a 0dBm output driver.

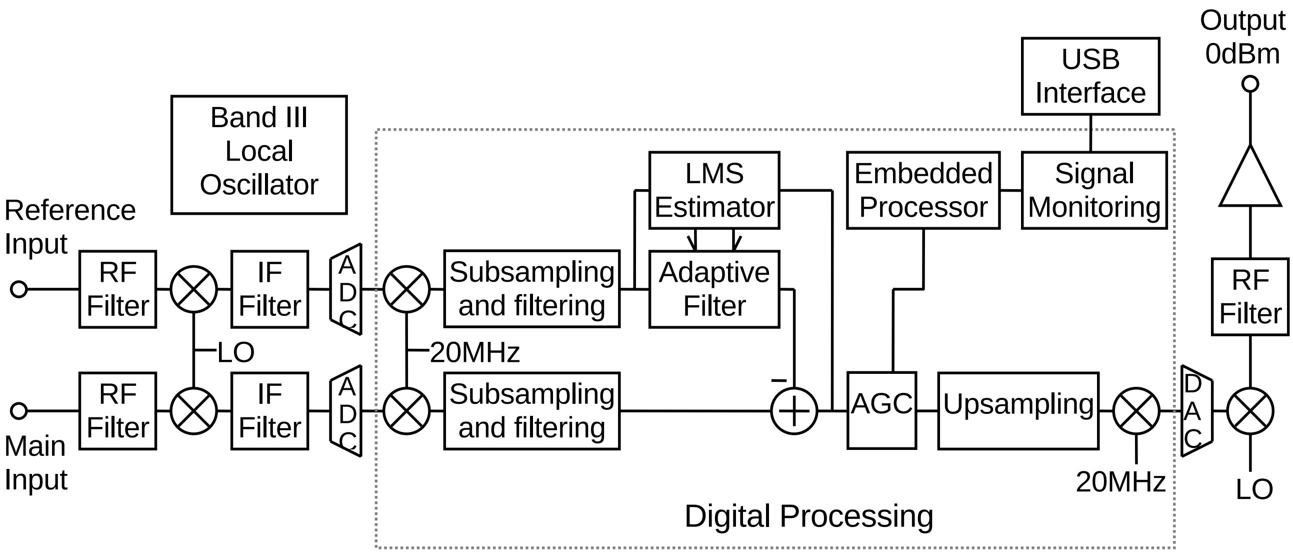

Figure 4 –Block diagram of the BBC digital on-channel repeater.

The wanted DAB signal on Band III, received using a directional antenna, is fed into the main input of the repeater unit. The first module is an RF filter designed primarily to reject an image frequency before downconversion. A high level mixer is then used to convert to a 20MHz IF where a high order LC IF filter is applied to remove most of the energy of the adjacent channels. The received signal may of course be buried under a feedback signal some 30dB stronger. In addition, the unfiltered remnants of the adjacent channels must also be accommodated in order to avoid clipping. Consequently, the design of the mixer and IF filter must ensure the lowest distortion and the highest dynamic range within the wanted bandwidth before the signal is digitised. The signal is sampled by a 14-bit analogue-to-digital converter running at 80MHz so that the quantisation noise is spread over the entire Nyquist bandwidth of 40MHz resulting in the effective signal to noise ratio of 93dB with respect to full scale within the useful 1536kHz bandwidth.

Once in the digital domain, the signal is converted to complex baseband, filtered and subsampled to 1.66MHz. It should be noted that adjacent ensembles are separated by as little as 176kHz, which imposes a sharp filter roll-off, resulting in non-linear group delay performance of the repeater at the edge of the ensemble. There follows a feedback cancellation block, which renders the signal suitable for re-broadcasting. The output level is stabilised by the AGC module, which is appropriately gated to avoid gain changes during the DAB null symbol. The signal is then upsampled, mixed up to an IF of 20MHz and converted back to analogue in a 16-bit converter. All digital processing is performed in a single Field Programmable Gate Array (FPGA) device, which executes approximately 3 billion fixed-point multiplications per second. A further up-conversion to Band III is followed by an image rejection band-pass filter and a 0dBm driver stage. This signal can then be routed to an external RF power amplifier and RF channel filter, and combined with the main transmitter output carrying an adjacent channel or directly applied to the transmitting antenna.

The reference signal obtained from a coupler in the antenna feed is processed in an identical manner to the main signal, as described above, up to and including the digital down-conversion and filtering. The next stage is the adaptive filter which produces the cancellation signal subtracted from the main input. Filter taps are calculated in an LMS estimator module.

The signal levels are monitored by an embedded microprocessor in the FPGA that controls the behaviour of the AGC circuitry. If an abnormal condition is detected, such as an overload or signal disconnection, the output of the repeater is reduced or muted. Important parameters, such as the length of the adaptive filter and the output signal level, can be adjusted by means of a USB interface, which is also used during field tests for real-time monitoring of filter taps and other internal signals on a laptop computer. A DAB demodulator was implemented in software and used to assess the quality of the spectrum and constellation of the retransmitted signal.

LABORATORY TESTS

In order to evaluate the repeater performance, a number of laboratory measurements and experiments were carried out at the home of BBC R&D in Kingswood Warren, Surrey, UK. First, an HP11759D channel simulator was used to measure the ability of the adaptive filter to track dynamically varying feedback between antennas. Different static and Doppler channels with multiple reflections were successfully cancelled by the repeater, depending on the speed of convergence and gain parameters. For example, feedback cancellation of 34dB could be achieved for channels with Doppler paths varying at 10Hz, equivalent to 13km/h at 225MHz.

During another test, involving a retransmission of 1W of DAB through a rooftop antenna, cancellation levels of 50dB were reached with the transmitted signal 30dB larger than the original received signal at the main input. Since no significant variability of the parasitic feedback was observed, the Doppler handling capability could to be reduced to 0.8Hz, sufficient to follow vibrations of the antennas caused by wind as well as movement of distant objects.

FIELD TRIAL

The first field test of the BBC on-channel repeater was conducted at the Mapperley Ridge transmitter site in Nottingham, UK. The site, containing a 1kW ERP transmitter for channel 12C (227.36MHz), was chosen due to problems in reception of channel 12B (225.648MHz) from Waltham 30km away. Referring back to Figure 2, the ratio of powers of signals 12B and 12C was too high to allow reliable reception within a 3.5km radius of the Mapperley site. Thus the objective was to transmit a 5W ERP signal on channel 12B, having received it from Waltham using a 3-element Yagi mounted on the transmitter mast. As shown in Figure 5 the output of the repeater at 0dBm was fed into a 40W DAB amplifier. The signal then passed through a 6-cavity Kathrein channel filter to a 10dB coupler to be combined with the signal on 12C. The reference signal was obtained from a 47dB coupler.

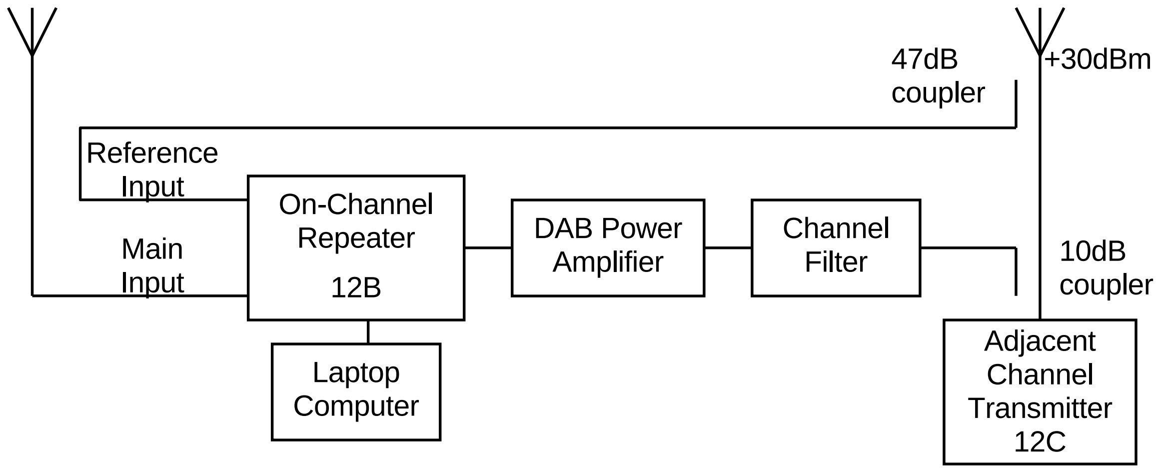

Figure 5 – On-channel repeater at Mapperley Ridge.

At Mapperley Ridge the isolation between the receiving and transmitting antenna was measured at 77dB, and the 12B signal from Waltham was at –40dBm. The total gain required for 12B, including the 10dB coupler and feeder loss, was 70dB to produce +30dBm output. The isolation was observed to change with time, possibly due to weather conditions, such as rain, fog and moisture on the ground.

Figure 6 shows the spectrum obtained from the receiving antenna. The signal on 12B is a sum of the feedback from the transmitting antenna and the original signal received from Waltham. It can be seen from Figure 7, which shows the signal at the transmitting antenna, that the spectrum of the 12B ensemble is flat, which indicates that the parasitic feedback has been removed. No noticeable degradation of signal-to-noise ratio was observed. A reception survey confirmed that the repeater enabled successful demodulation of 12B in the vicinity of the Mapperley Ridge site.

Due to the modest gain requirement and higher than expected antenna isolation, the full capability of the repeater was not exercised. The measured level of cancelled interfering signal was, depending on weather conditions, 1dB to 7dB lower than the level received from Waltham. This should be compared to the result quoted in the previous section, where the feedback was 30dB higher than the wanted signal. However, an attempt to re-broadcast without cancellation would have resulted in instability, or at best in very non-linear frequency response.

It was also observed that, although the repeater introduced a delay of only 20µs, some DAB receivers used for the reception survey had occasional problems with time synchronisation in areas where the signals from Waltham and Mapperley Ridge were of comparable strength. Further work is needed to quantify how pervasive this problem might be.

CONCLUSIONS AND FUTURE WORK

The BBC prototype of a digital on-channel repeater demonstrated the suitability of digital echo cancellation techniques for extending coverage of OFDM broadcast services. Effective antenna isolation was increased by up to 50dB, sufficient to achieve significant system gain values while maintaining good signal-to-noise ratio. No problems with stability were observed during field tests, as parasitic antenna coupling was changing very slowly, largely due to weather conditions.

A similar, but computationally more powerful, repeater can also be designed for DVB-T, but the multilevel QAM modulation imposes stricter limits on signal-to-noise ratio. Hence, the system gain cannot be as high as in the case of DAB, especially if 64-QAM is used. To achieve faster and more precise tracking of feedback, other algorithms, such as Fast RLS could be implemented, at the expense of much greater computational complexity.

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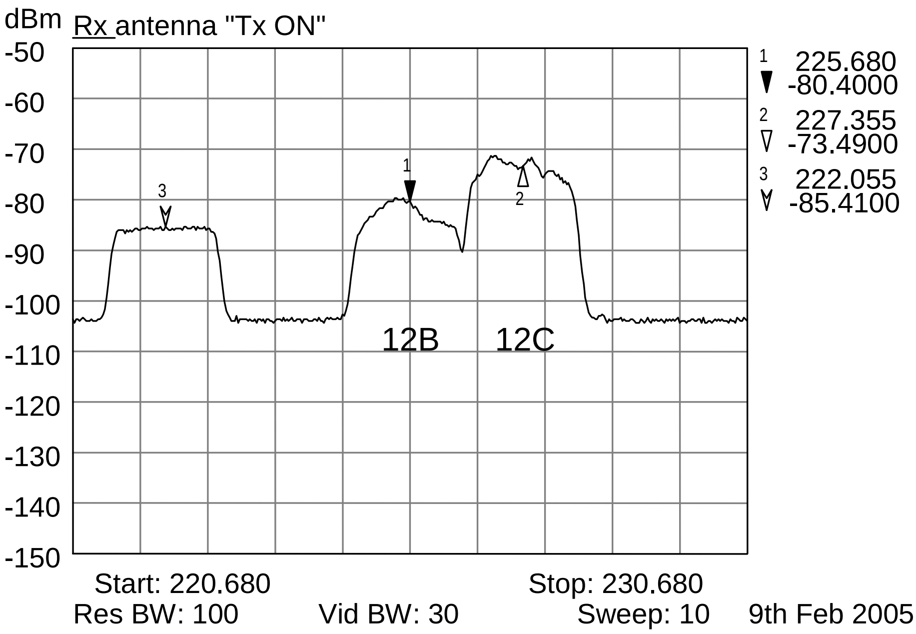

Figure 6 – Signal at the receiving antenna (after 30dB coupler).

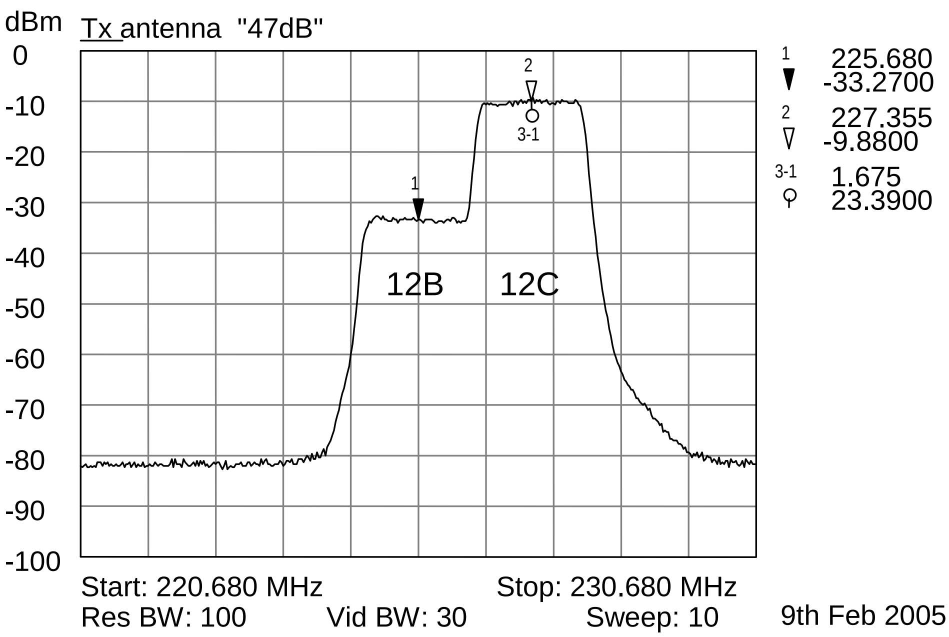

Figure 7 – Signal at the transmitting antenna (after 47dB coupler).