REDUCING THE ENERGY CONSUMPTION OF TERRESTRIAL DAB TRANSMISSION

P. D. Kesby[1], R. H. M. Poole[2], A. Wolmarans[2], P. G. Brown[1]

[1]Arqiva, UK, [2]BBC, UK

ABSTRACT

The requirement to develop sustainable broadcast platforms that support global net-zero targets increases year on year. This paper discusses initiatives developed by the BBC and Arqiva to reduce power consumption in their terrestrial DAB broadcast network. In some cases, it is possible to improve efficiency without complete replacement of the transmitters.

Improvements in transmitter technology now allow optimisations to be considered that were not practical previously. Modern transmitter design often takes advantage of Doherty techniques and power supply optimisation. However further reductions may be possible, going beyond previous assumptions, with negligible effect on consumer reception.

This work evaluates the opportunity for a trade-off between modulation quality and energy consumption. The impact of modulation error ratio (MER) on DAB reception has been investigated through theoretical modelling and validated using laboratory testing with channel simulation. The results from these studies show that the impact on reception of reduced MER can be less than previously assumed. Field trials in the operating network, using a transmitter with reduced MER, showed a small to negligible impact on reception. This points to power savings that can be made across DAB networks.

The combination of MER change and related power supply optimisation is expected to reduce the total energy consumption of the existing in-service Doherty transmitters by between 12 and 17%. This approach will be rolled out to 165 present Doherty transmitters during 2024. This technique could be considered for use in future transmitter equipment designs.

INTRODUCTION

Many broadcasters have recently developed carbon reduction and net-zero strategies. Reducing energy consumption will help meet net-zero targets with significant financial and carbon reduction savings**.** The BBC has recently published its carbon reduction strategy and plans to reduce its energy consumption on UK terrestrial platforms by 28% by 2030 [1]. The BBC terrestrial transmission networks in the UK are owned and operated by its transmission partner Arqiva who together with the BBC are investigating a range of energy saving initiatives. However, measures taken must be proportionate to the benefits whilst maintaining minimal impact on the audience. Improving the efficiency of the terrestrial networks can be achieved by deploying new, more efficient transmitters but it can be preferable to optimise existing, already operational equipment. Improving existing equipment avoids the carbon impact and cost of replacement. Finally, efficiency measures must maintain compliance with regulatory requirements and must not compromise the long-term reliability of equipment.

The BBC DAB network comprises more than 400 transmitters, which provide greater than 97% coverage of UK homes [2]. The network was launched in 1995 with an initial 31 transmitters. Several subsequent phases of additional deployment have resulted in a dense medium-power network which covers most of the major roads and homes in the UK. The staggered deployment of equipment over this period has resulted in a range of equipment types and designs. Some early designs exhibit system electrical efficiency of approximately 10 to 20%, whilst more modern designs achieve 40% or better. In this paper the term efficiency refers to system electrical efficiency which is the conducted RF power provided to the antenna divided by the total energy used by the transmitter, including internal cooling.

A DAB OFDM signal without clipping typically exhibits >10 dB peak-to-average power ratio (PAPR). A lack of headroom in the amplifier can cause signal clipping, creating in-band and out-of-band (OOB) intermodulation products (IPs). In-band IPs reduce signal quality, whilst OOB IPs, if not removed, can exceed regulatory emissions limits. Therefore, initial Class-AB amplifier deployments were designed to operate with a large headroom in the amplifier power supply to satisfactorily manage the peaks, resulting in transmitter electrical efficiencies in the region of 10 to 20%. Because of coverage and regulatory requirements (on a site-by-site basis), many transmitters operate below their rated power. The combination of this with limited capabilities to optimise the power supply resulted in relatively poor efficiency. Later strategies were developed which allowed a small reduction in the PAPR in the modulator (or amplifier) combined with power supply optimisation in the amplifier, hence improving the efficiency of the transmitter. A step change in DAB transmitter efficiency was achieved with the introduction of Doherty designs [3], combined with flexible power supply optimisation, which led to efficiencies greater than 35%.

A measure of signal distortion is modulation error ratio (MER), described in more detail later in this paper. More aggressive clipping at the transmitter causes greater signal distortion, and lowers the value of the MER. The statistical nature of the time-domain waveform will result in the peaks occurring infrequently. Therefore, transmitter design now allows for a lowered PAPR, thus accepting a small increase in signal distortion. Modern power supply designs can be adapted to remove the unused headroom (even when the configured RF conducted power is significantly below the manufacturer’s rated power), lowering the voltage power supply rails and improving efficiency. Typically network operators target 25 to 30 dB MER for output signal quality to protect coverage. This study has investigated the relationship between MER and coverage and has confirmed that the MER can be lowered from earlier targets to 20 dB with negligible effect on service coverage. Allowing a lowering of MER enables a further reduction in power supply headroom and improvement in transmitter efficiency.

As described above, the BBC DAB network comprises a range of transmitter technologies jointly consuming approximately 10 GWhr/year. The aim of this study is to reduce the energy consumption of the already installed Doherty transmitters (consuming 2.4 GWhr/year), with adaptable power supply designs, combined with a reduction of the transmitter MER signal quality to 20 dB. This approach cannot be practically replicated at the remainder of the older transmitter sites but could be implemented in new transmitter designs.

SIGNAL QUALITY AND MODULATION ERROR RATIO

The DAB signal comprises 1536 carriers each modulated with quadrature phase-shift keying (QPSK). The notional carrier phase changes each symbol period. A constellation diagram showing the amplitude and phase of all carriers superimposed is shown in Figure 1 below, in the diagram on the left. This is the ideal situation; in practice, noise on the signal causes the constellation points to move away from the ideal.

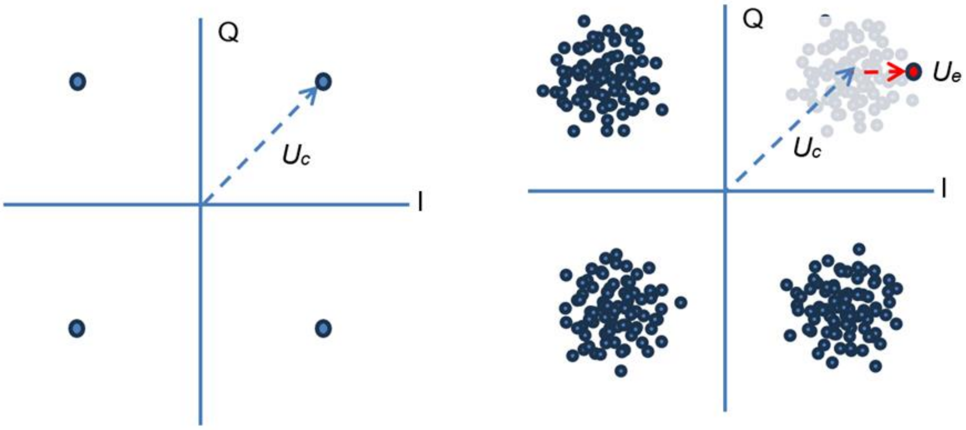

Figure 1 - Idealised and practical DAB QPSK constellation

The 'correct' carrier amplitude and phase is U_c, and the deviation is U_e for one particular carrier. As mentioned earlier, the overall signal quality is quantified by the modulation error ratio, or MER [4]. It is defined as the ratio U_c/U_e averaged over all N carriers, using RMS addition and expressed in dB:

$$MER_{dB} = 20\,log_{10}\sqrt{\left(\frac{1}{N}\right)\sum_{n=0}^{N-1}\left(\frac{U_c}{U_{en}}\right)^2}$$

Here, U_{en} is the error associated with the n^{th} carrier.

It appears that the MER defined by this equation is equivalent to the signal-to-noise ratio (SNR) of the signal. However, DAB uses differential QPSK, where the carrier phase of the previous symbol is used as the reference for the present symbol. Any noise on the previous symbol then gets added to that of the present symbol, so doubling the effective noise:

$$MER_{dB} = SNR_{dB} - 3\;dB$$

In practice, the receiver has its own noise contribution, as well as that introduced by the transmitter. The impact of the additional transmitter noise contribution can be quantified by calculating the increase in transmitter power which would be required to compensate for that additional noise.

The model is shown in Figure 2 below:

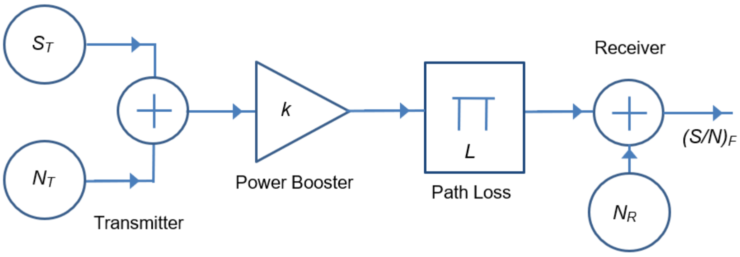

Figure 2 - Transmitter power increase k to compensate for MER degradation.

The transmitter generates a wanted signal S_T and noise N_T. There is a path loss L between the transmitter and receiver, and we assume that the transmitter power needs to be boosted by a fraction k to overcome N_T. The receiver itself introduces noise N_R, and needs a minimum signal-to-noise ratio $(S/N)_F$ (the failure point) to decode the signal.

In the absence of transmitter noise, we have

$$(S_T/L)/N_R = (S/N)_F \tag{1}$$

at the failure point. (S_T/L) simply represents the transmitter power reaching the receiver. With transmitter noise N_T present, and the transmitter power boosted by k,

$$\frac{kS_T/L}{kN_T/L + N_R} = (S/N)_F. \tag{2}$$

Although we have defined k as the increase in transmitter power needed to overcome the noise associated with decreased transmitter MER, we can equally use its reciprocal, $1/k$, to characterise the effective loss of power if the actual transmitter power is kept constant. This effective power reduction represents a coverage reduction.

Rearranging the equation and noting that $S_T/N_T = 2 \times MER$, and $(S_T/L)/N_R = (S/N)_F$ at the failure point:

$$\frac{1}{k} = 1 - \frac{(S/N)_F}{2MER} \tag{3}$$

In a Gaussian channel, the $(S/N)_F$ can be taken as 7 dB [5]. More realistic fading channels, which include impairments such as multipath and Doppler, are used for network coverage planning, and for these $(S/N)_F$ in the range of 13 to 15 dB are used for different fading channel profiles. The plots below show the predicted effective loss of transmitter power for failure points of 7, 13 and 15 dB.

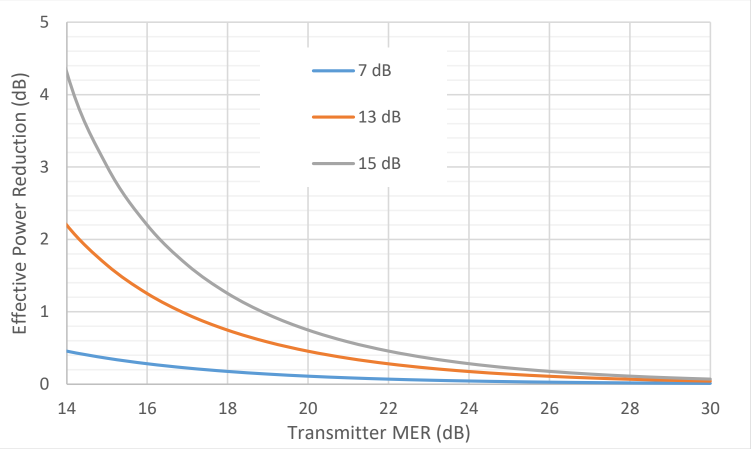

Figure 3 - Calculated transmitter power increase to compensate for MER degradation

For the Gaussian case, the results are very encouraging. Assuming we start with baseline MER of 25 dB, then reducing this to 20 dB MER, causes the effective loss of power to be a negligible 0.1 dB. Further reduction in MER to 15 dB results in effective loss of power of less than 0.4 dB. However, the situation looks much worse for the fading channels, with the effective loss of power being 3 dB at 15 dB MER for the channel with $(S/N)_F$ of 15 dB.

MEASURING THE IMPACT OF CHANGING MER IN SIMULATED CHANNELS

The effective power reductions under different channels were tested in laboratory experiments. DAB signal files were generated from baseband ETI reference files in the

WorldDAB library [6], generating IQ samples using the open source ODR-DabMod modulator [7]. These were processed in software using the Rapp AM-AM compression model [8] to approximate the effects of linear amplifier compression. A series of files were created with reduced PAPR, ranging from 1.9 to 13 dB. The corresponding MER for these files ranged from 8.4 to 38 dB.

The DAB signal files were selected and played out using a Rohde & Schwarz Broadcast Test Centre signal generator. Fading channel characteristics were then applied, followed by the addition of noise, all within the same instrument. Three fading channel profiles were used: Gaussian channel (no fading), rural area (RA) and typical urban (TU) multipath [6]. The noise level was adjusted while the wanted signal level was kept constant, so that the signal-to-noise ratio at the receiver could be adjusted for testing.

For each DAB signal file, the noise level was adjusted until the receiver BER is at the reference threshold. As used here, BER refers to pre-Viterbi MSC BER reported by a Rohde & Schwarz ETL Analyser. This raw BER is a pseudo-channel BER [9] since it relies on the output of the Viterbi FEC to detect errors rather than the audio source data stream. The specific value for the reference BER threshold is not critical in these tests but a value of 5×10^{-2} was chosen [10]. Measuring BER is complicated by the variability inherent in fading channels. The BER fluctuates widely with the channel gain and, to achieve a stable mean value, a very long averaging period is used. Because of the large number of points, measurement accuracy was traded against averaging time. This caused some scatter in the data.

The test results are shown in Figure 4 for the Gaussian and TU fading channels. Similar results were also found for the RA fading channel. This shows the increase in C/N needed when the transmitted MER is degraded. This is equivalent to the effective power difference calculated in the previous section, equation (3). The Gaussian channel results were as expected and showed good agreement with the calculation (solid line). However, the results for the fading channel do not follow the calculations based on the fading channel C/N (dashed line). Instead, they also follow the Gaussian channel calculation. This is a beneficial result since it means the MER can be reduced far lower than would be the case if the behaviour was aligned with that expected of the fading channel.

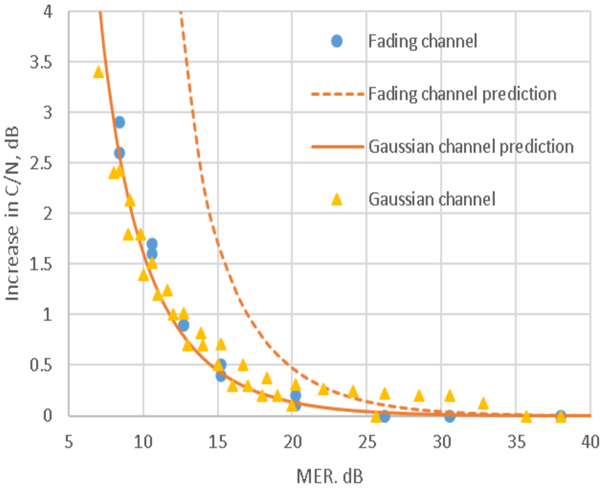

Figure 4 - Experimental verification data for Gaussian and TU fading channel.

THE IMPACT OF CHANGING MER IN A FADING CHANNEL

The practical test results above show that the fading channel behaviour is similar to that in a Gaussian channel. The explanation is as follows. Three noise sources contribute to the total noise at the receiver. The channel noise, made up of environmental noise and receiver thermal noise, can be assumed to be constant in all channel types. The transmitter noise is not constant at the receiver because it is subject to the loss in the channel, so it is directly proportional to the received signal level. This means that in a fading channel, when the signal level is low, the transmitter noise power is also proportionally reduced. When the fading channel signal level is high, the transmitter noise power is increased.

Figure 5 illustrates the Gaussian channel on the left, at the failure point C/N_F, with the total noise being the sum of the channel noise and transmitter noise. On the right are three representations of the fading channel at three separate instants. In the first case, the signal has faded to a lower level, with the transmitter noise faded to the same extent. The BER is now poor, primarily because of the low signal strength relative to the channel noise, with the transmitter noise being less significant. In the second case, the signal is at the same level as for the Gaussian channel, and the noise contributions are the same; hence the impact on the BER is the same. In the third case, the signal level is greater. Although the transmitter noise and total noise are also greater, the signal is greater still, and the BER is better.

Most bit errors are associated with C/N values near their minimum because the BER has a very sharp dependence on C/N [11]. What happens at higher C/N values is largely irrelevant. In a fading channel a higher C/N is needed for a given average BER. In our present example, we can imagine raising the signal level by about 3 dB, so that our worst-case C/N now corresponds to that of the Gaussian channel at the failure point. Figure 5 now looks like Figure 6.

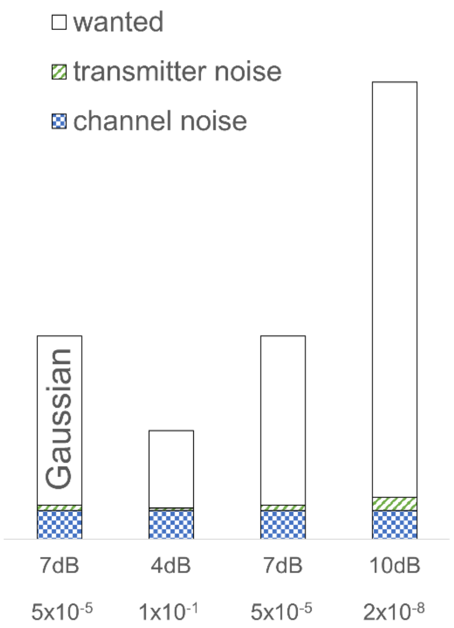

Figure 5 - Noise in Gaussian and fading channels
BER is post-Viterbi BER

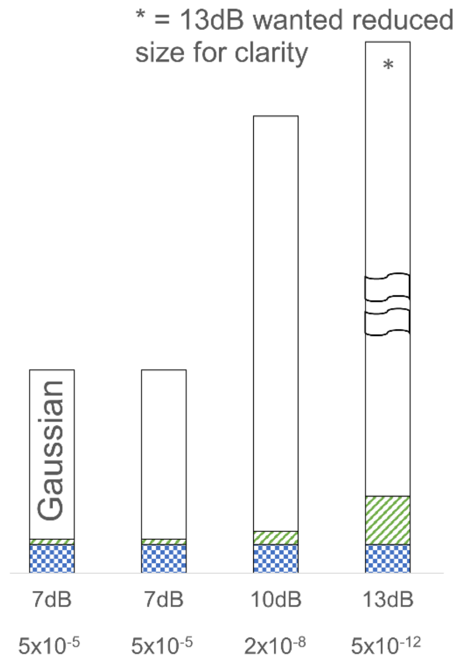

Figure 6 - Noise in Gaussian and fading channels, increased power in fading channel
BER is post-Viterbi BER

Since the fading channel at its worst looks just like the Gaussian channel at the failure point, we can assume that the effect of transmitter noise is the same in Gaussian and fading channels. Hence the same k-factor applies (the increase in transmitter power needed). A simulation of a more realistic Rayleigh distributed fading channel has been carried out for a range of MER from 10 to 40 dB. The transmitter power increase required was consistent with equation 3. In conclusion, as a convenient rule-of-thumb, the effective loss of transmitter power can be taken as 0.1 dB for an MER of 20 dB, in practical channels.

COVERAGE IMPACT OF MODULATION ERROR RATE

The nominal coverage impact on a single isolated transmitter site can be estimated using the Hata propagation model [12]. The impact of the suggested 0.1dB effective change in transmitter power is to reduce the coverage radius to 99.2% of the original radius, for an effective transmitter antenna height of 100m. A circular coverage area is correspondingly reduced to 98.4% of the original area.

But this calculation assumes a cut-off threshold in coverage, where reception is either acceptable or unacceptable. In practice there is coverage variability due to propagation variation. For mobile outdoor reception the DAB network is typically planned for 99% locations served at the edge of coverage. With standard deviation assumed to be 4 dB [5] and effective change in transmitter power of 0.1 dB, then the coverage percentage at the edge is reduced from 99% to 98.93% locations. The overall average percentage locations served within the circular coverage area [13] reduces from 99.83% to 99.82% locations, a difference of only 0.01% locations. In practice the propagation will be affected by larger scale variations in terrain and clutter, and there will be overlaps between neighbouring transmitters in the DAB single frequency network (SFN), so the practical coverage impact will deviate from these assumptions. A field trial was carried out to investigate the impact in a practical network environment.

An operational transmitter site at Clun in Shropshire, Figure 7, was selected, in the BBC UK national SFN. This allowed testing in both edge-of-coverage and transmitter overlap conditions. The dominant coverage area includes rural roads and village buildings. There is additional overlap coverage into the market town of Craven Arms. The transmitter (manufactured by COMMTIA) was operating on the BBC frequency 12B 225.648MHz with Effective Radiated Power (ERP) 600W. The transmission format is DAB Mode 1, UEP-3.

Figure 7 – Clun Transmitter Site

Coverage was evaluated using a series of drive tests in the coverage area. The test receiver configuration was a Factum Radioscape Observa Field Monitor with a ¼λ whip antenna magnetically mounted on the vehicle roof. The receiver can log useful parameters including signal strength, pre-Viterbi BER and GPS location. The number of transmitters identified, and their Transmitter Identifier Information (TII) codes, were used to confirm which transmitters contributed to the measurements. The TII codes were used to identify overlap areas where multiple transmitters were received in the SFN.

Three transmitter MER options were configured and tested to ensure compliance with the spectrum mask required by the ETSI standard [14].

The MER configurations were:

- 25dB MER, representative of existing network configurations
- 20dB MER, proposed reduced MER
- 15dB MER, extreme reduction for test purposes

Each of these MER configurations were tested in three reception scenarios:

- Strong dominant single-transmitter coverage
- Edge-of-coverage single transmitter
- Transition into overlap area with multiple transmitters

The routes were driven separately three times for the three different MER configurations. The measurement samples are averaged over grid pixels for analysis. The percentage of measurement samples where the BER is less than the 5×10^{-2} threshold is calculated for each pixel (before Viterbi error correction). Figure 8 shows the pixels identified as the baseline where percentage coverage is 99% for MER 25 dB, for 50-metre pixel size.

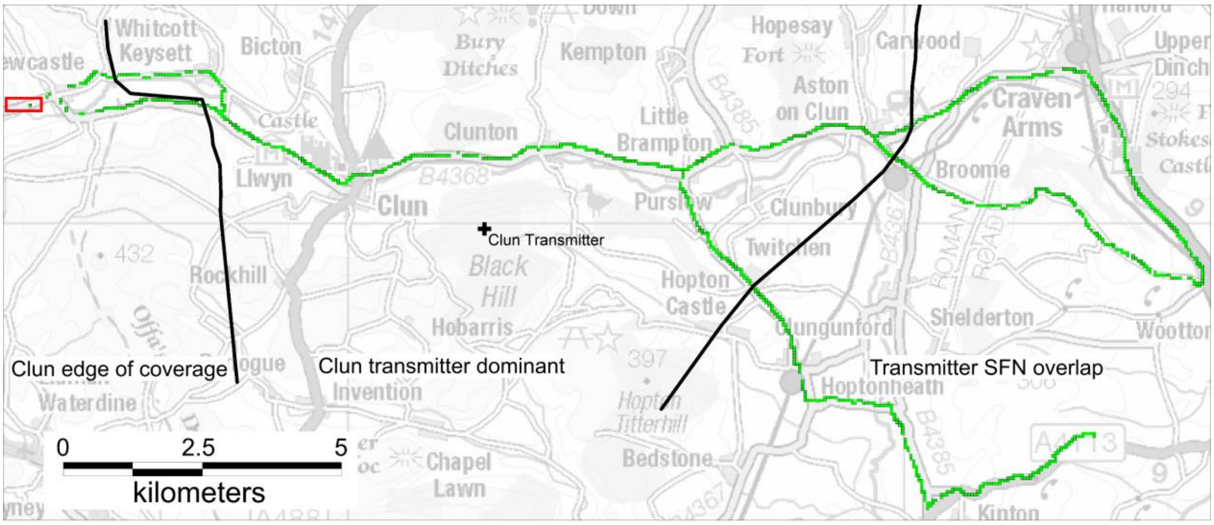

Figure 8 - Clun drive route.

The results in Table 1 show the percentage coverage on the route, in terms of measurement sample points. This is restricted to pixels where the 25 dB MER results meet the 99% criterion. The overall average percentage points shows that the coverage degradation is <0.1% for both 20 dB and 15 dB MER. This is less than the variation between repeated measurements of the same route, so impact is not practically measurable.

MER	Percentage sample points
15 dB	99.92%
20 dB	99.96%
25 dB	100.0%

Table 1 - Percentage of sample points where pre-Viterbi BER is better than 5×10^{-2}.

For the above three cases, no measurable difference between the transmitter MER options was found for the scenarios with a dominant strong single transmitter (Clun) or in the scenarios where there was overlap of up to 6 transmitters. However, at the edge of the SFN coverage there were small differences.

A more detailed view of the edge of coverage is calculated for a 670m sub-section of the drive route at the western edge of the area (red rectangle in Figure 8). The vehicle is travelling east to west, from good reception to bad reception. BER is averaged with a 50m moving window. Table 2 shows the average BER on this edge of coverage segment, and the changes in the distance for which the BER exceeded the 0.035 and 0.05 thresholds, compared to the 25dB case. The differences in distances between the MER modes depends on where on the route the analysis is carried out, but the distances are small in all cases.

MER	15 dB	20 dB	25 dB
Average BER	0.0369	0.0351	0.0334
Distance BER>0.035	-44m	-13m	
Distance BER>0.05	-84m	-55m	

Table 2 - Percentage of sample points where pre-Viterbi BER is better than 5x10^{-2}.

Figure 9 shows the moving average BER (over 50m) along this section of the route for the three transmitter MER options. There is some variability between the result for different MER options, even in areas of low BER. This will be due to propagation variability between successive drive runs, and the small variations in the path that the vehicle travels along the road. The BER is higher in some parts of this route for 15dB and 20dB MER, with 15dB MER being the worst.

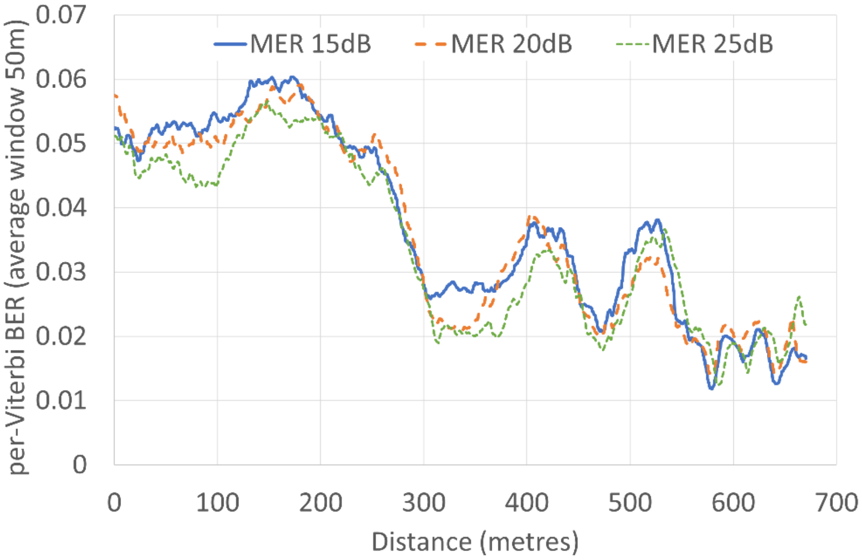

Figure 9 - Clun edge of coverage average pre-Viterbi BER for different MER configurations, travelling east to west.

The measurements show that the difference in BER between MER 25 and 20 dB is small. The differences are comparable with the variability between different drives on the same road. Subjective listener comments showed that the difference between 25 and 20 dB MER was not perceptible. The change from 25 to 15 dB was slightly perceptible at the extreme edge of coverage locations, with audio break-up earlier by 10 to 20 metres.

IMPLEMENTATION OF ENERGY SAVINGS

Using a combination of MER reduction from 25 to 20 dB, combined with optimising the power supply, can result in a worthwhile reduction in transmitter energy consumption. Careful analysis has been undertaken which has identified which types of transmitters already operating in the network can benefit from this optimisation approach. Evaluation of the BBC DAB network has confirmed that this approach is best suited to the modern Doherty design. The combined energy usage of the Doherty only transmitters in the network is approximately 2.3GWhr/year. This modern type of transmitter can be remotely optimised which will save transmitter site visits and can be implemented without a further carbon cost.

Overall reduction in energy consumption between 12 and 17% can be achieved, depending on the frequency of operation and other factors. Power supply changes resulting from the MER change should yield 5 to 11% reduction in consumption. Remaining benefits will be achieved due to other power supply optimisation carried out simultaneously. This approach will be rolled out to 165 present Doherty transmitters during 2024. Other types of transmitters in the existing network will not be modified using these techniques. This is because the changes to the power supply arrangement are far more intrusive and would require extensive site-by-site modification where in many cases the benefits could be negligible.

CONCLUSIONS

In this paper we have presented an approach to reducing the energy consumption of DAB broadcast transmission, by improving the transmitter efficiency. A change in the transmitted signal quality, in the form of a small degradation in modulation error rate, combined with the optimisation of the power supply, enables the transmitters to operate in a more energy efficient configuration. This approach will be part of improvements to 165 BBC Doherty transmitters which should reduce energy usage by between 12 and 17%. This technique can also be considered for inclusion in future transmitter design. Theoretical analysis, laboratory simulation and field tests have shown that this approach has a negligible effect on practical reception. Compliance with regulatory limits can be maintained.

REFERENCES

1. "BBC sets out path to Net Zero by 2030". Press Release. BBC. October 2021.
2. Digital radio and audio review, Department for Culture, Media & Sport. April 2022, Section 6.15.
3. Cripps, Steve C, RF power amplifiers for wireless communications. Vol. 250. Norwood: Artech house, 2006.
4. Rohde & Schwarz 2013. DAB Transmitter Measurements for Acceptance, Commissioning and Maintenance. Rohde & Schwarz Application Note. July 2013
5. EBU 2018.Guidelines for DAB Network Planning. EBU Tech 3391. May 2018.
6. ETI Reference Library. WorldDAB.
7. ODR-DabMod modulator. Opendigitalradio.org.
8. Rapp, C., 1991. Effects of HPA-nonlinearity on a 4-DPSK/OFDM-signal for a digital sound broadcasting system. Proceedings of the 2nd European Conference on Satellite Communication, 22-24.
9. Schramm, R., 1997. Pseudo channel BER-an objective quantity for assessing DAB coverage. EBU Technical Review, pp.23-30.
10. EBU 2020. Measuring Techniques for DAB Coverage Performance. EBU Tech Report 051. April 2020.
11. TR 101 758, Digital Audio Broadcasting (DAB); Signal strengths and receiver parameters; Targets for typical operation, ETSI, November 2000.
12. Hata, M 1980. Empirical formula for propagation loss in land mobile radio services. IEEE Transactions on Vehicular Technology 29.3: 317-325.
13. Reudink D O. Chapter 2 in Jakes, William C., and Donald C. Cox, eds. Microwave mobile communications. Wiley-IEEE press, 1994.
14. ETSI EN 302 077 Transmitting equipment for the Digital Audio Broadcasting (DAB) service; Harmonised Standard for access to radio spectrum.

ACKNOWLEDGEMENTS

The authors acknowledge the contribution of colleagues: Michael Clark, Marcin Rydlinski and Lindsay Cornell (BBC), Will Partridge, Thomas Smith, Mark Abbot, Julian Marlow (Arqiva)