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Wireless delivery of audio services - final report

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About Plum

Plum offers strategy, policy and regulatory advice on telecoms, spectrum, online and audio-visual media issues. We draw on economics and engineering, our knowledge of the sector and our clients' understanding and perspective to shape and respond to convergence. Phil Sheppard (Clear Technology Consulting) has contributed to this project as a Plum Associate.

About this study

This study for the BBC provides predictions of the level of mobile network coverage in the context of broadcast audio distribution to listeners. An examination of technical coverage criteria also forms part of this work.

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Summary

Listeners are increasingly using cellular mobile networks to access live broadcast radio services through smartphone apps, as an alternative to traditional broadcast networks (FM and DAB). This has implications for broadcasters in terms of the degree to which cellular coverage can replicate that of existing services, the comparative quality of service of different delivery mechanisms and the potential for such mobile networks to substitute for traditional broadcast networks.

This study provides an initial estimate of the evolution of mobile network coverage in the UK over a 15 year timeframe, from the specific perspective of the provision of streaming audio services.

It finds that cellular coverage, at a data-rate suitable for the streaming of live audio services, is already comparable to that provided by national DAB radio networks. A precise comparison will require more detailed technical measurements, as recommended in this report, and liaison with DAB planners to ensure that availability targets and other assumptions are aligned.

Unlike broadcast networks, the reliability of audio services streamed over cellular networks may also be constrained by network congestion in high-traffic areas. Detailed statistics on cell-loading are not generally available; although our tentative judgment is that problems may be restricted to relatively few hotspot areas, it may be necessary to implement measures to prioritise audio streams if the most robust quality of service is to be achieved.

Although coverage from at least one mobile operator is available over 96.8% of UK land area, the useful coverage for specific listeners will be dictated by individual operator coverage levels, and these are significantly lower; areas in which all mobile networks are available cover 85.2% of the UK land area. This figure is set to increase substantially in the next five years, and it is expected that coverage from all operators will reach 93.0% by 2026. It is not considered likely that there will be any significant changes to cellular coverage, in the context of audio streaming delivery, beyond that date.

Cellular operators are currently rolling out 5G networks which will initially supplement, and eventually replace, existing 4G networks. While 5G brings a great increase in the capabilities and flexibility of cellular networks for new services, the impact on coverage and user experience for the relatively low bitrates required by streaming audio will be slight. For the purposes of first-order estimation of coverage, 4G and 5G delivery can be considered interchangeably.

These figures mask significant complexity; the values quoted correspond to the use of a typical handset, and a streaming app that offers a robust degree of buffering. For poorly-specified hardware and software, the relevant ‘all networks’ coverage figures may be as low as 66% (current) and 84% (2026) respectively.

Broadcast coverage figures have traditionally been expressed in terms of population coverage (i.e. households served). In 2017, after significant expansion, the BBC national DAB service covered 97.4% of UK households. By comparison, 98.0% of homes are covered by all cellular networks for audio streaming to typical devices (but only 79.8% with less capable hardware and software).

The variation in these figures is a caveat against interpreting any coverage figures too rigidly. This is true of traditional broadcast delivery, but even more so for cellular services, where there are many more variables involved, most of them not under the control of broadcasters. Undertaking a formal technical investigation of the statistical nature of streaming coverage thresholds is one recommendation of the present report.

1 Introduction

For nearly a century, radio has been delivered as a 'linear' service over dedicated transmission networks. Consumer behaviour is, however, changing rapidly as listening moves to IP-based forms of delivery, whether over fixed or mobile networks.

This document is the final report for a study, commissioned by the BBC as part of the DCMS 'Radio and Audio Review' that aims to describe how the coverage of cellular mobile networks is expected to evolve over the next 15 years. This information will inform judgments as to the extent to which IP audio delivery over mobile networks will provide a substitute for traditional broadcast delivery.

In developing our models, it has been necessary to consider the appropriate technical coverage criteria to adopt; this is not a simple judgment because (i) much of the necessary information is not readily available and (ii) it may be fundamentally impossible to predict audio streaming coverage using the simple data relating to wanted signal strength that has been made available through Ofcom. A more complex approach that accounts correctly for the dynamics of interference and cell-loading may be required, and this is beyond the scope of this initial study.

It is intended that the main body of this report should be accessible to the general reader, with technical detail given in the appendices.

2 The delivery of broadcast radio services

2.1 Traditional broadcast networks

The broadcast delivery of radio programmes has evolved over almost 100 years, from beginnings in the medium frequency (MF) and low frequency (LF) bands using AM, to delivery of FM services in Band II VHF spectrum in the 1950s and to DAB radio at Band III VHF frequencies in the 1990s.

Each new technology offered greater overall capacity and, potentially, higher audio quality, but the model of free-to-air delivery and a transmission network based on a relatively small number of 'high-power, high-tower' transmitters[1] remained unchanged.

The coverage of DAB multiplexes is still increasing in the UK, with the continuing addition of low-power relay sites (Figure 2.1 & Table 2.1). The figure illustrates the problem, common to all terrestrial wireless networks, that coverage improvement becomes incrementally harder as the network grows. One constraint on network expansion for DAB is that self-interference within the national 'Single Frequency Networks' (SFN) will limit the temporal availability[2] of services in some areas.

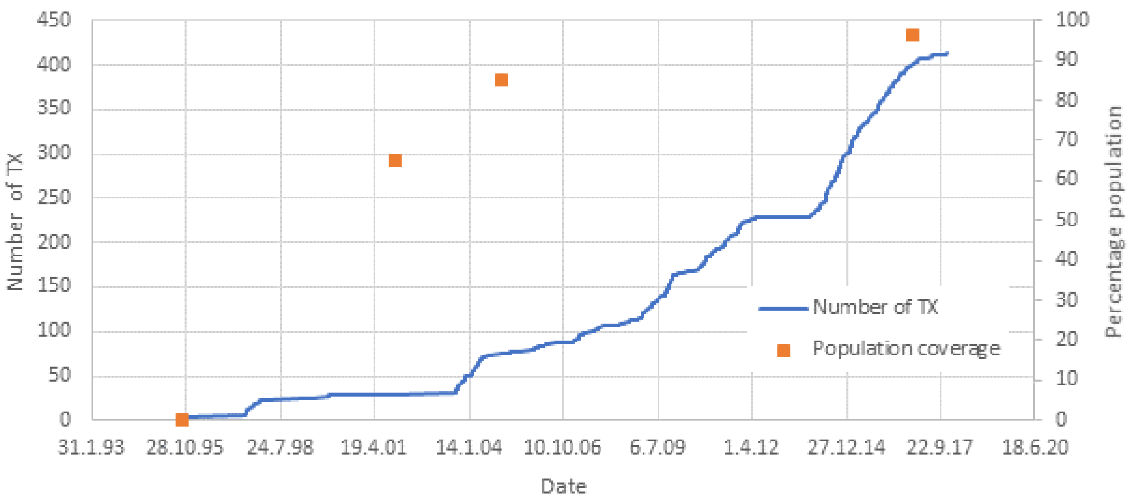


Figure 2.1: DAB national network (BBC) roll-out

Coverage location	UK-wide BBC	UK-wide commercial DAB		Local DAB
		Digital One	Sound Digital	
Homes (indoor)	97.4%	91.7%	82.6%	91.0%
Major roads	87.4%	80.2%	72.6%	75.2%

Table 2.1: : DAB Population Coverage by multiplexes (March 2019[3])

A concern often expressed about DAB is that it is ill-suited for use by small, local broadcasters, particularly in cases where there may be few services requiring space on a multiplex with limited geographical coverage. In an

[1] Albeit with each network in turn being made more dense with the addition of medium- and low-power relays.
[2] i.e. in certain weather conditions, enhanced propagation of signals from distant parts of the UK network may cause mutual interference.
[3] From Fig 4.16, Ofcom 'Media Nations' report (Media Nations: UK 2019 (ofcom.org.uk))

attempt to address these concerns, the UK government and regulator (DCMS & UK Ofcom) supported a series of trials to investigate the feasibility of providing 'small-scale' DAB services using cheap consumer-grade equipment and open-source software. While early generations of DAB coders and transmitters relied on custom hardware, it is now straightforward to use standard computers to perform most of the coding in software and to make use of the growing availability of general-purpose software-defined radio (SDR) hardware for transmission.

A total of ten trials are currently running; Ofcom have recently invited[4] applications for operational licences for local commercial, community and specialist music stations.

2.2 Unicast cellular delivery of broadcast services

The use of existing 4G networks to provide unicast delivery of radio content is a dramatic change to this model of service delivery, with each receiver requiring a subscription to a mobile network, and with content delivered on a one-to-one basis. In addition, the frequencies used by the networks are significantly higher than those used for broadcast delivery, and the networks dramatically more dense.

These factors all have an impact on potential coverage and listener experience; in lieu of national roaming agreements, the subscription model implies that listeners cannot necessarily make use of the network offering the best coverage in a particular area, while the use of unicast delivery may lead to capacity constraints and service disruption in data traffic 'hotspots' (often the same as vehicle traffic hotspots). The higher frequencies used by the networks imply that diffraction losses[5] will be greater, with potentially deeper 'shadow' areas and the need for larger numbers of base stations, even where capacity consideration do not require them.

In rural areas, the density of base station deployment will generally be constrained by cost considerations; coverage will, therefore, tend to be uplink limited. This will result in smaller coverage areas for unicast delivery than would be the case were the same sites to be used for broadcast downlink delivery only.

To set against these considerations, the 4G LTE[6] and 5G NR physical layers offer an evolving range of options for diversity, beamforming and MIMO techniques, with which both capacity and coverage can be enhanced. The need for very dense networks in urban areas, primarily to provide capacity for traditional cellular applications, will also imply a high level of geographical coverage, and a diversity of illumination into buildings. Although the higher frequencies give greater diffraction loss, they can also penetrate building apertures more efficiently than FM radio frequencies, and have lower levels of impulsive electrical interference[7].

2.3 Multicast cellular delivery of broadcast services

The cellular industry, represented in the 3GPP standards body and broadcasters have been working together for some years to add broadcast-specific functionality to cellular standards. The BBC, in particular, has made very significant contributions to the standardisation of multicast functionality in the 4G and 5G standards.

Although 4G/LTE includes an FeMBMS (Further Evolved Multimedia Broadcast Multicast Services) mode in Release 14, which, in principle, allows dedicated broadcast-mode operation, this is constrained in many parameters, including the permissible network topologies and by the absence of support for MIMO.

[4] https://www.ofcom.org.uk/manage-your-licence/radio-broadcast-licensing/small-scale-DAB-licensing
[5] The reduction of signal strength as users are shielded by terrain, buildings, etc
[6] LTE ("Long Term Evolution") and NR ("New Radio") are the technologies used by 4G and 5G systems. See Annex A for a full glossary.
[7] See Appendix D

The greater flexibility of the 5G NR physical layer offers the opportunity to add a more capable FeMBMS offering, permitting broadcast features such as multicast, free-to-air (SIM-free) reception and wide area (high-power, high-tower) transmissions, with seamless switching between unicast/multicast/broadcast modes.

The Horizon 2020 project, 5G-Xcast' (https://5g-xcast.eu/) ran from 2017-2019, and focussed on the development of broadcast and multicast within the 5G standards. UK partners included BBC R&D, together with BT, the University of Surrey and Samsung UK. This work has been influential in the 3GPP standardisation process, which has adopted architectural enhancements for 5G multicast-broadcast services as a current study Item. This should allow the inclusion of multicast and broadcast capabilities in the existing 5G architecture in Release 17 of the standard, currently scheduled for late 2021. These new features, however, are primarily for small scale and single-cell deployments and not large scale SFNs or receive-only devices.

Despite enthusiasm from broadcasters, and a developing technological capability within the 3GPP standards, the commercial response to MBMS has, to date, been lacklustre; this is discussed below.

3 Cellular radio in the UK

3.1 The evolution of cellular mobile radio in the UK

Initial analogue (1G) networks were rolled out by Vodafone and Cellnet from 1985. In 1993/4, GSM (2G) was launched by the two existing operators at 900 MHz, and by the new entrants, One2One and Orange at 1800 MHz.

A further new entrant, Three UK, launched a 3G-only service in 2003, being followed by the existing four networks in the next year ('one2one' having re-branded as 'T-mobile'). All operated, initially, in the 2100 MHz band.

In 2010, T-mobile and Orange merged under the new brand 'EE'. In 2012 EE was the first to launch a 4G network, using its 1800 MHz spectrum; the other operators followed in 2013, following the Ofcom auction of 2.6 GHz spectrum and the 800 MHz band previously used for TV broadcasting (the 'Digital Dividend').

In 2012, Vodafone and O2 set up a joint venture, Cornerstone Telecommunications Infrastructure Limited (CTIL), to manage shared mast infrastructure; Orange and EE have a similar subsidiary, Mobile Broadband Network Limited (MBNL).

5G services were launched by EE in a limited number of cities in May 2019, with the other networks following over the next 12 months.

3.1.1 Spectrum

In the past, different generations of service have used distinct spectrum bands (e.g. 900 and 1800 MHz for 2G, 2.1 GHz for 3G), but all operators are now 're-farming' 2G and 3G spectrum for use by 4G and 5G services. This, together with the results of takeovers and re-assignment of spectrum has led to a complex pattern of spectrum use. The tables below attempt to provide a summary of the current situation.

Table 3.1: Spectrum available for mobile use in the UK

3GPP Band	Frequency band	Alternative name	Downlink	Uplink	Notes
1	2100 MHz	UMTS	2110 – 2170	1920 – 1980	Original 3G band
3	1800 MHz	DCS-1800	1805 – 1880	1710 – 1785	Original 2G band (Orange, One-2-One)
7	2600 MHz	2.6 GHz	2620 – 2690	2500 – 2570	
38	2600 MHz	2.6 GHz centre-gap	2570 - 2620	2570 - 2620	TDD. EE only
20	800 MHz	Digital dividend	791 – 821	832 – 862	
32	1500 MHz	L-band, SDL[8]	1452-1492	n/a	EE, Vodafone
8	900 MHz	GSM	935 - 960	890 - 915	Original 2G band (Vodafone, Cellnet)
8	900 MHz	E-GSM	925 – 960	880 – 915	
78	3400 MHz	C-band	3300-3800	3300 - 3800	TDD. Only 3.4-3.6 auctioned to date

[8] Supplementary Downlink

3GPP Band	Frequency band	Alternative name	Downlink	Uplink	Notes
40	2300 MHz	S-band	2300 - 2400	2300 - 2400	TDD. to O2 in UK

As the disjointed 3GPP numbering suggests, these bands represent only a portion of those in use worldwide. This complex, and geographically-varied pattern of spectrum use represents a growing problem for handset manufacturers; the need to accommodate many frequencies has tended to reduce the overall efficiency of handset antennas.

The use of these bands by UK operators is summarised in the table below.

Table 3.2: Frequency bands by operator

MHz: 3GPP band:	800 B20	900 B8	1500 B32	1800 B3	2100 B1	2300 N40	2600 B7,B38	3400 N78
Vodafone	4G	2G, 3G, 4G	SDL[9]	4G	3G, 4G		4G	5G
O2	4G	2G, 3G, 4G		4G	3G, 4G	4G		5G
Three	4G		SDL	4G	3G, 4G			5G
EE	4G			2G, 4G	3G, 4G		4G	5G

Further spectrum auctions, at 700 MHz and 3.6-3.8 GHz had been due to take place in Spring 2020, but are currently delayed by COVID-19 (and a possible legal challenge).

An important aspect, not shown in Table 3.2, is the total amount of spectrum available to each operator in each band. For example, spectrum at 800 and 900 MHz has propagation characteristics that make it well-suited to providing wide-area rural coverage or good building penetration; EE and Three, however, hold only 5 MHz of spectrum at 800 MHz, compared with 10 MHz each by Vodafone and O2, who can also re-farm their holdings at 900 MHz. To set against this, EE hold the largest amount of spectrum overall.

3.2 Current 4G coverage status

Ofcom's 'Connected Nations' report provides an annual summary of fixed and mobile connectivity in the UK, updated on an annual basis. Mobile network coverage information is provided by the four Mobile Network Operators (MNO) at 100m pixel resolution. Although the individual prediction models vary, a limited number of snapshot measurements have been made by Ofcom to provide some confirmation of the submitted data.

For 4G data, the coverage threshold is based on a 98% probability of achieving a 2Mbit/s download rate. An Ofcom study in 2018 equated this to an outdoor RSRP[10] of -105dBm, with a 10dB loss assumed into buildings or cars (i.e. an RSRP of -95dBm is required to provide indoor or in-car coverage. These levels are also applied to 4G voice coverage, and serve to define the overall threshold of 4G coverage in the Ofcom reports. These levels are not, necessarily, appropriate thresholds for the delivery of radio services, and this is discussed in detail in Section 4 of this document.

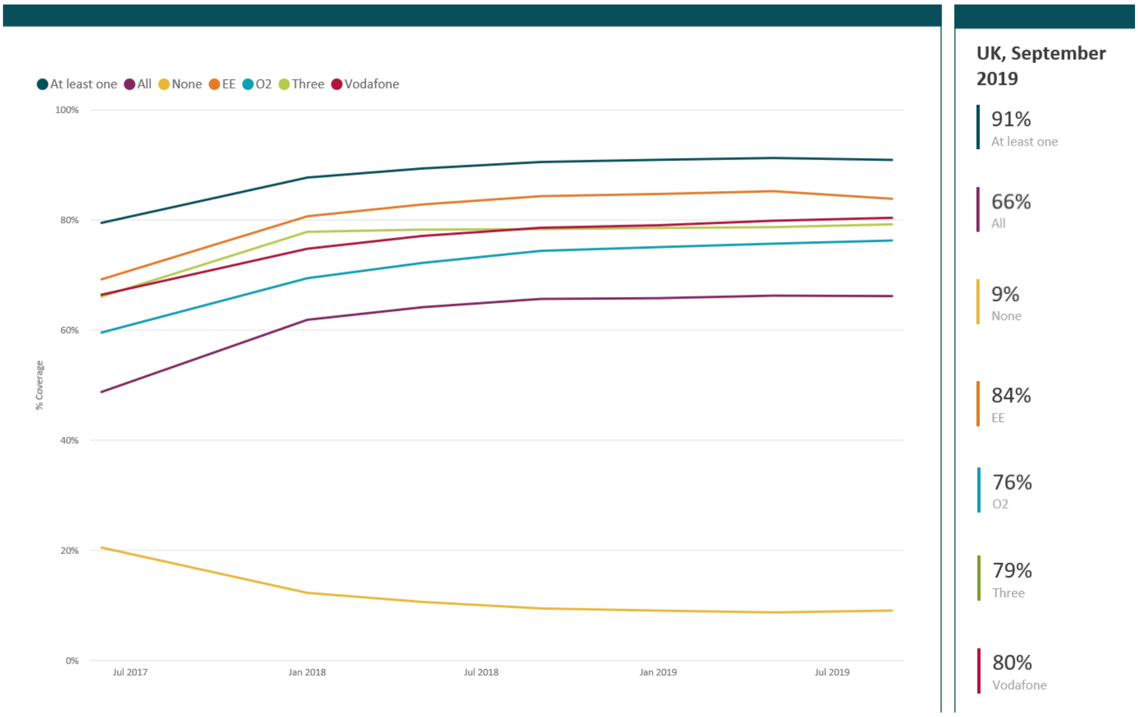
Comparison over time is complicated by the fact that the metrics presented by Ofcom have changed over the years (e.g. road coverage was broken down as 'motorways' and 'A & B roads' in 2016, but as 'motorways and A-roads' and 'B-roads' in 2017. Similarly, coverage models used by operators have changed, which has introduced

[9] Supplementary DownLink
[10] Reference Signal Received Power – the average power of a Resource Element (RE) carrying a cell-specific reference signal

artificial discontinuities in coverage estimates (e.g. by EE between 2018 and 2019, giving an apparent reduction in road coverage).

Notwithstanding these minor issues, the overall pattern of change in geographic coverage for 4G data is very clear, with all individual networks showing flattening growth concerging on geographical coverage levels between 76% and 84%.

Figure 3.1: 4G geographic data coverage (Ofcom 'Connected Nations 2019' interactive report)



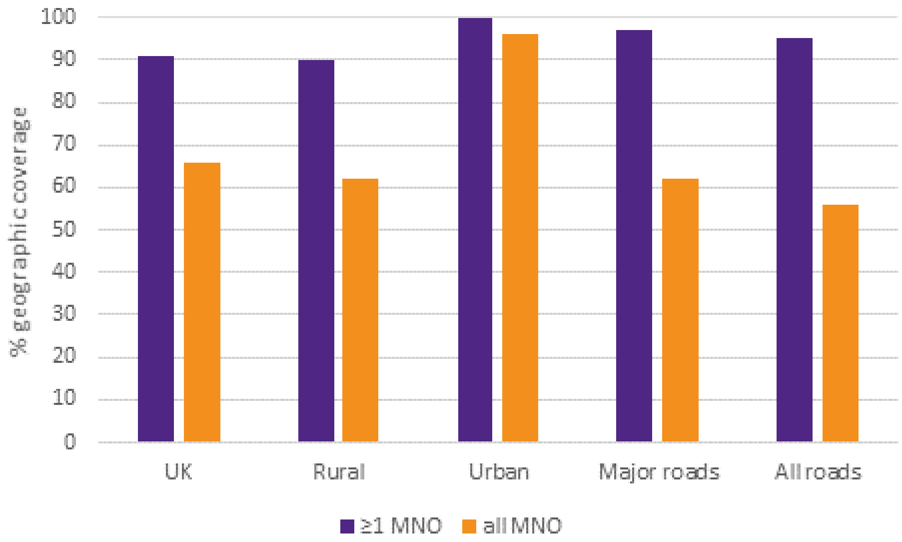
The differences between nations are significant, as would be expected given the large unpopulated areas without roads in Wales and, especially, Scotland.

Figure 3.2: 4G data coverage by nation (Plum, from Ofcom 2019 data)

Similarly, the gulf between urban and rural coverage statistics is clear; despite the perception of the country as rather highly urbanised, the extent to which overall UK geographic coverage is determined by the rural figure should be noted.

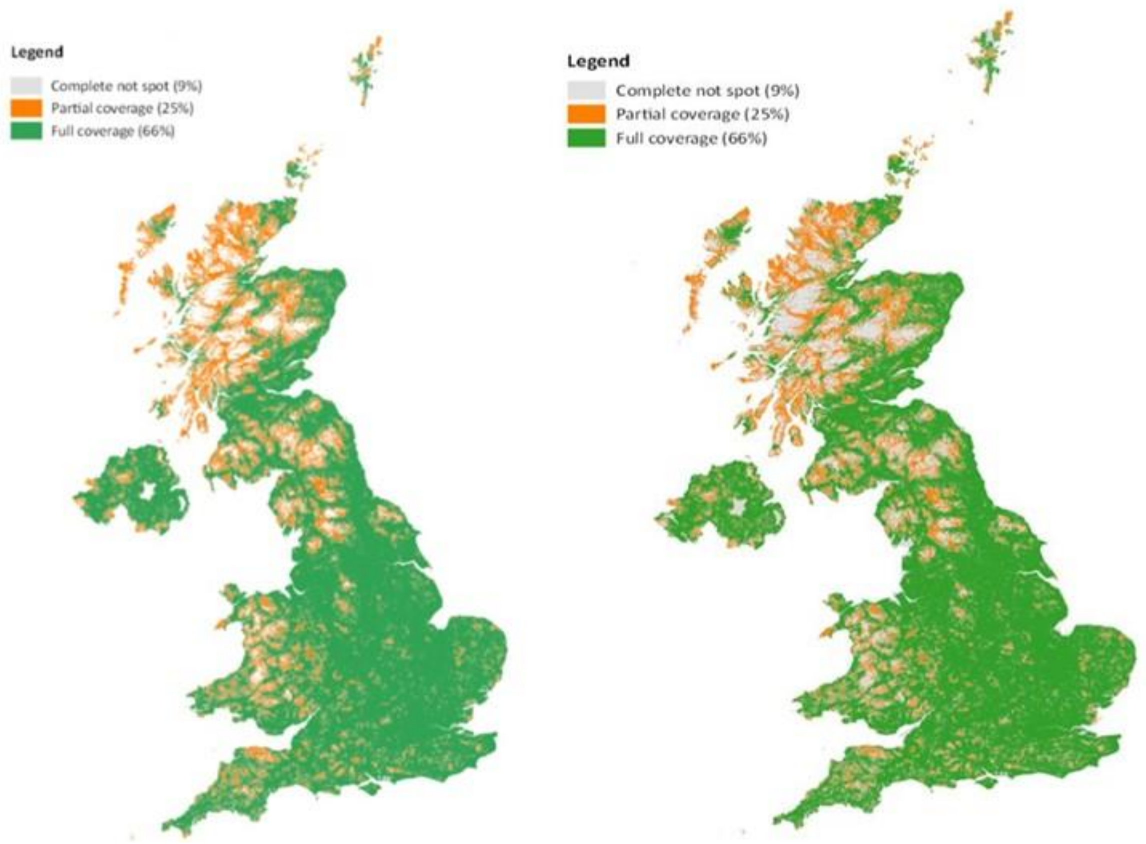
For road coverage in particular, it is relevant to note the significant difference between coverage by 'all operators' and coverage by 'at least one MNO'; this statistic is to relevant discussions on national roaming, SIM-free broadcast delivery and the Shared Rural Network (SRN).

Figure 3.3: 4G data coverage by geotype (Plum, from Ofcom 2019 data)



The asymptotic trend in geographical coverage is clear from the coverage maps accompanying the Ofcom 'Connected Nations' reports for 2018 and 2019.

Figure 3.4: Mobile network coverage in 2018 (left) and 2019 (right) (Ofcom)



The figures above give a clear indication of the extent of coverage deficiencies in upland areas of the UK. Ofcom had originally planned to include coverage obligations to address these deficiencies in the auctions for 700 MHz and 3.6 GHz spectrum.

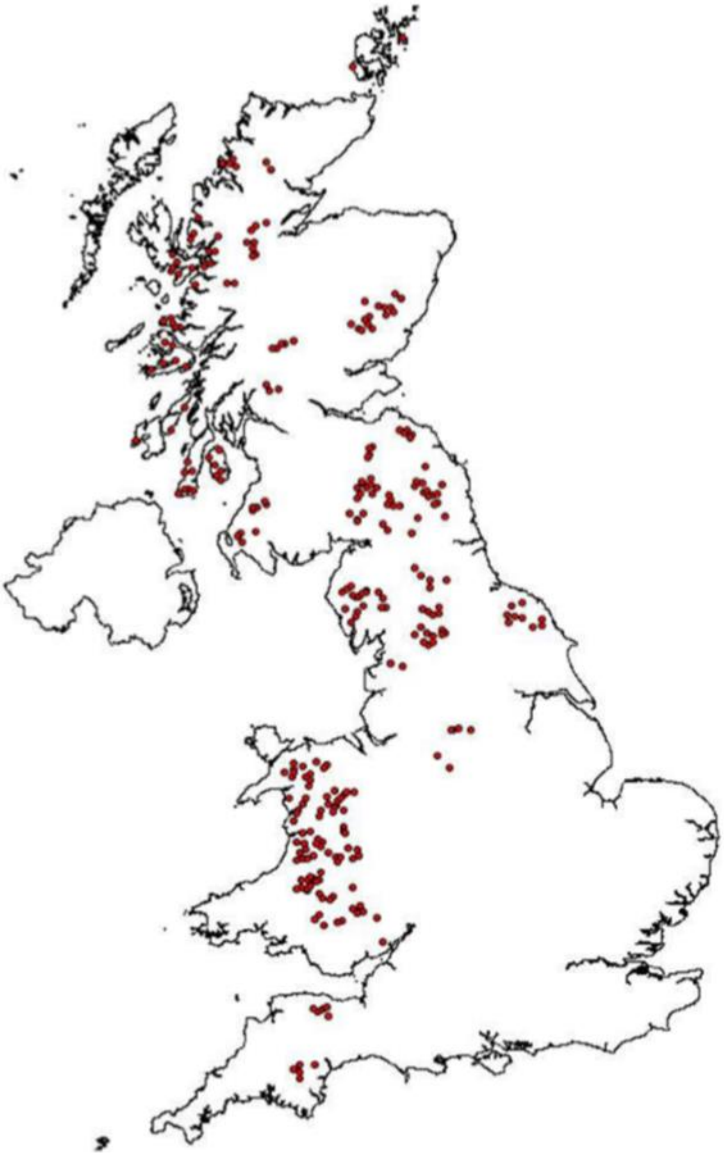
An alternative proposal from the mobile industry for a 'Shared Rural Network' (SRN), has now been agreed. This will commit the industry to specific coverage targets, with the government contributing additional funding and access to the infrastructure of the Emergency Services Network.

3.3 The Emergency Service Network

A decision was made in 2015 that the existing emergency services communications network ('Airwave', which uses TETRA technology) will be replaced by a network (the 'Emergency services Network, ESN) based an a commercial 4G network, with appropriate security, quality-of-service and functionality enhancements. EE was awarded this contract, and has since rolled out some 500 new sites in rural areas to bring its geographic coverage of the UK to 84% of the UK landmass, the highest of the four MNOs.

In addition to the sites provided by EE, the Home Office are charged with rolling out a further 292 'Extended Area Service' or EAS sites in areas that are not deemed commercially viable. These sites will cover around 1% of the overall UK land mass. These sites, which will be integrated with the EE network for ESN purposes, may also be used by commercial networks. These EAS sites were originally expected to have been commissioned by the end of 2019, but have been subject to significant delays, with only 20% of sites built by that date.

Figure 3.5: Location of EAS sites (Three submission to Ofcom[11])



The Shared rural Network agreement (see below) includes provision for all MNOs to have equipment on the EAS sites. While practical issues (e.g. planning permission for appropriate masts designs) may preclude this in some cases, it is expected that at least a 1% improvement to all MNOs will be achieved by using EAS sites

3.4 The Shared Rural Network

In the Future Telecoms Infrastructure Review (DCMS, 2018) the government set a target for 4G coverage to reach 95% geographic coverage of the UK by 2022. This target was seen as commercially unrealistic, as a requirement for individual operators, by Ofcom and others, and the coverage obligation eventually incorporated in the 700 MHz auction was reduced to 92% and finally to 90%. The possibility that 'national roaming' might be mandated as a way of improving individual users' experience of coverage may have prompted the ultimate agreement between the four MNOs and the Government on a 'Shared Rural Network' (SRN). The original 95% target will still be achieved, however, for 'any MNO' coverage.

[11] https://www.ofcom.org.uk/__data/assets/pdf_file/0030/146856/three.pdf

The SRN, announced on 9th March 2020 is intended to improve poor rural phone coverage through the sharing of existing sites (to address 'partial not-spots' or PNS, where at least one, but not all MNOs have coverage) and the building of new, Government-funded, sites in areas that are currently unserved by any MNO and are not deemed to be commercially viable ('total not-spots' or TNS). The £1bn funding will be split almost evenly, divided between the Government and the MNOs, and should ensure 95% geographical coverage of 4G services[12] by 2026.

The primary SRN criterion relates to pure geographical coverage, but the agreement also contains an additional requirement to cover a certain amount of roads and premises. As geographical coverage is the primary criterion and is enforced in MNO spectrum licence obligations, the incentive for the MNOs will be to maximise geographic coverage rather than improving road and premises coverage. The inclusion of some minimum road and premises targets within the SRN agreement partially mitigates that incentive to cover uninhabited geography rather than roads or premises.

The most significant coverage changes that will result from the SRN implementation relate to partial not-spots (PNS); i.e. locations where not all MNOs have coverage and extending this to all operators. The headline targets will increase the area where services are available from <u>all operators</u> from 66% to 84% by 2024 (with every operator having at least 88% coverage individually) and when combined with the Government-funded TNS programme, the geographic coverage where <u>any MNO</u> has signal from 91% to 95% by 2026. The TNS programme will be focussed on Scotland and will add 3% geographic coverage to that nation (equivalent to 1% of the UK).

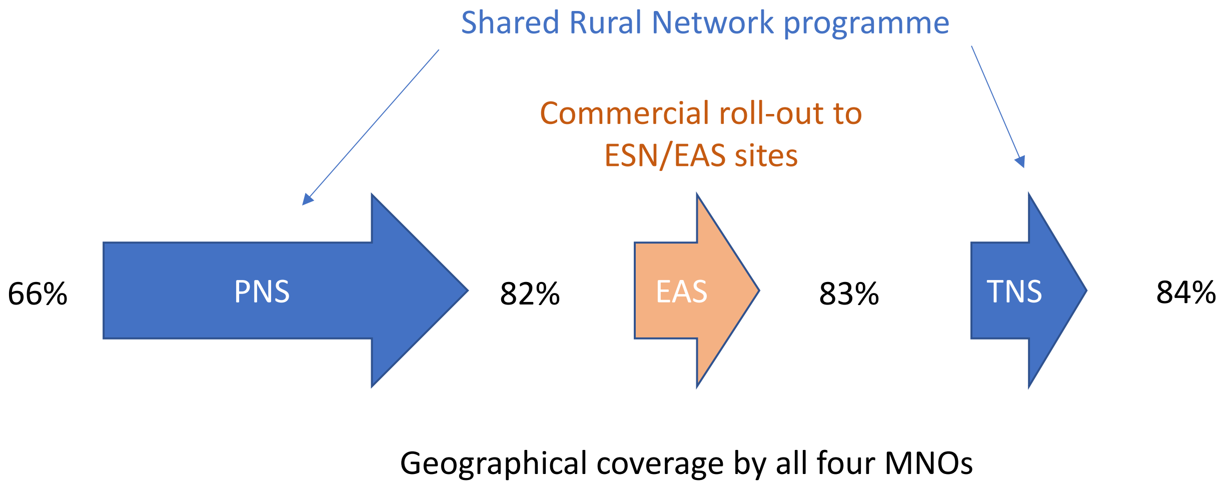
The TNS programme, which is funded by a grant to MNOs by the Government, and managed by DMSL[13] is distinct from the EAS programme (see above) which is a Home Office project. Each programme (EAS and TNS) is expected to add 1% geographical coverage[14].

Despite such challenges as COVID-19 and new Government policies regarding Chinese equipment vendors, all the indications, in mid-2020, are that SRN is on target for achieving the schedule. The incentives are high with spectrum license obligations and the timetable is realistic for such a deployment.

In Scotland, a further scheme aimed at providing coverage in total not-spots, the Scottish 4G Infill programme[15] (S4GI) is running in parallel with the TNS programme. This scheme, with £25m of funding by the Scottish Government and the European Regional Development Fund was set up in 2018 and has 15 sites under construction, with one live and 20 more envisaged.

[12] by 'any operator'
[13] Digital Mobile Spectrum Limited, a company jointly-owned by the UK MNOs.
[14] The 1% figure applies, strictly, to the high-rate threshold only. The coverage at low-rate will be greater, but offset by the larger overlap with existing services.
[15] https://www.gov.scot/publications/scottish-4g-infill-programme-map

Figure 3.6: Coverage gain ('high-rate') expected from the SRN and EAS projects



One caveat concerning the SRN, and other rural parts of the cellular network, is that if rural fixed broadband has poor coverage in these areas, it is possible that cells may be significantly congested due to home and business use. Given that much of this infrastructure will be new, it is hoped that the capacity gains available from the introduction of the latest 4G technologies and the availability of 5G will minimise any such bottlenecks.

3.5 Summary

The table below summarises the changes to UK geographical coverage of generic 4G cellular services expected as a result of the commitments described above.

Table 3.3: Expected changes to UK geographic 4G coverage

MNOs	2019	2024	2026
Any	91%		≥ 95%
Each	76-84%	≥ 88%	≥ 90%
All	66%		≥ 84%

4 Technical coverage criteria

4.1 Introduction

To make any assessment of network coverage, whether by measurement or prediction, it is clearly necessary to define appropriate criteria. For any radio network, some of these criteria will need to be defined in statistical terms, because of the inherent variability of signals with time and location.

With an analogue service, the starting point in defining these standards will be in terms of subjective quality (audio signal-to-noise ratio) and the required reliability (e.g. percentage of locations covered within a prediction 'pixel'). 'Acceptable' quality is often very hard to define, as it will depend on environment (quiet living room, car, building site) and hardware (stereo Hi-Fi or portable radio); what different listeners find acceptable may vary by some 20dB (a hundred-fold variation in received power).

For digital services, the subjective quality will generally be predetermined by the chosen coding scheme, and will generally show a rapid degradation from 'perfect' to 'no service', albeit with some 'burbling' over a range of a couple of decibels. The key parameter to define is, therefore, the required reliability, which will often be greater than an analogue service, due to the 'cliff edge' degradation in quality.

In both cases, it will be necessary to make some assumptions about the sensitivity of the receiving system. Although receivers show variations in sensitivity, these are generally much less significant than the variation in antenna (aerial) performance. In planning FM radio services, for instance, the initial assumption was that listeners would install rooftop antennas with a gain of at least 3-6dBi, but almost all receivers now will use small 'whip' aerials near the ground and with a gain at least 10dB lower. In-car DAB installations can have very poor antenna performance, especially in the case of low-profile 'fin' antennas, or antenna elements printed on the windscreen. Similarly, smartphones show a very wide variation in performance; antenna gain tends to reduce as more spectrum bands needs to be catered for, though this is offset to some extent by the trend for larger screen sizes which coincidentally allows for bigger and more efficient antennas. A high-profile case was the *'antennagate'* incident when Apple's iPhone 4 featured an antenna that simply failed to work if the device was held in certain ways, but it is still the case that phones show a very wide variation in performance[16] [17].

In the present study, we are aiming to allow comparisons to be made between different delivery technologies, and this is complicated by the fact that the three services considered have very different characteristics; the relatively gentle degradation of FM, the sharper 'burbling' transition of DAB and the impact of buffering on a service streamed over a cellular network, which may completely hide drop-outs of many seconds (at the price of time delays or user frustration when first selecting a stream).

The sections below review the technical criteria used to define coverage for each service; a more detailed technical treatment for the cellular case is given in the Appendix.

4.2 FM Broadcast

The coverage criteria for FM radio were first developed in the 1950s on the basis of home reception, with rooftop antennas and a quiet listening environment. Typical reception conditions are now very different but the limits are essentially unchanged. This represents a pragmatic approach which, for instance, assumes that less

[16] https://www.stelladoradus.com/wp-content/uploads/2018/04/ComReg1805.pdf

[17] https://www.ofcom.org.uk/__data/assets/pdf_file/0015/72231/mobile_handset_testing_1v01.pdf

efficient antennas tend to be associated with smaller sets & less critical listening (e.g. a rod antenna on a portable set used in the kitchen).

Current Ofcom policy[18] states that an area is covered if both "*the median signal field strength, within the area of analysis (typically a 'pixel' of dimensions approximately 100m x 100m) assessed at a height of 10m, is at least 54dBµV/m*", and if the field strength is also sufficiently high to protect against interference from other services.

In practice, it is generally the latter criterion – interference protection – that defines the extent of a service area. Although less pronounced than for UHF television, high-pressure weather conditions are often associated with an enhancement of signals from distant transmitters. This can lead to problems in rural areas, where little interference might be expected and is a severe constraint on service planning. The VHF national network was planned to be free of interference for 99% time.

The current criteria ensure high-quality reception, e.g. for classical music with a traditional 'hi-fi' system, but are certainly conservative in the context of typical portable or mobile reception, and compressed material. A listener in a car may consider a much lower quality perfectly usable, even if degraded by some noise, interference or multipath[19] distortion. In considering the 'usable' service area of FM services, field strength limits of 48dBµV/m (in-home) and 42dBµV/m (vehicle) are often assumed.

4.3 DAB broadcast

For the main DAB networks, Ofcom assume a field strength requirement of 63 dBµV/m for indoor service and 54 dBµV/m for mobile reception. The network is planned for 99% time and 99% location availability[20]. These values were refined[21] from earlier assumptions in 2012, and take into account the statistical variability of propagation, receiver performance, interference, etc. The indoor limits were informed by the practical experience of listeners in around 60 households over a two-month period. A significant issue for the planning of national DAB services is that of network self-interference; while signals from multiple local transmitters will add constructively to provide 'network gain', beyond a certain distance signals from other transmitters will fall outside the DAB system 'guard interval' and cause interference. This is normally only an issue in times of enhanced signal propagation.

As noted in Appendix B, understanding listener experience for a particular coverage threshold is complicated by the very variable performance of DAB receivers and antennas. In particular, the adoption of after-market DAB car radios was hampered by the very low efficiency of some of the antennas provided.

4.4 4G cellular

To allow a meaningful comparison to be made between 4G/5G delivery and traditional broadcast platforms demands a careful examination of the technical coverage limits to be employed. In the 'Connected Nations' study, Ofcom currently base their headline estimates of 4G coverage on the criteria of '*a 98% chance of getting a download speed of at least 2Mbit/s*' or "*of nearly all 90-second telephone calls being completed without interruption*" and make the assumption that these requires an RSRP of -95dBm (indoor or in-car) or -105dBm (outdoor). Lower speed data, defined as ≥ 200 Kbit/s, is assumed to require RSRP values 10dB lower.

This may well be an appropriate generic limit for typical 4G use, but must be re-examined for (a) the specific case of unicast audio delivery and (b) to allow a direct comparison with DAB or FM coverage estimates. In DAB

[18] https://www.ofcom.org.uk/__data/assets/pdf_file/0018/54621/analogue-coverage-policy.pdf
[19] Interference between the direct signal and strong reflections from terrain or buildings, causing distortion to FM reception
[20] For roads. The 63 dBµV/m threshold corresponds, nominally to 80% indoor location availability in suburban areas,
[21] See https://www.ofcom.org.uk/__data/assets/pdf_file/0020/37190/dab_statement.pdf

planning, for instance, temporal and location availabilities of 99% are required, and it should be established that any 4G or 5G criteria are commensurate with this.

The technical limits associated with 4G cellular radio are examined in more detail in Appendix B.3. Although we have been able to undertake some informal testing as part of the present work (see Appendix C & D), it is strongly recommended that a formal exercise be carried out to determine the appropriate coverage thresholds for cellular audio streaming services, and to characterise the variability in performance associated with both hardware and software elements.

Based on our, necessarily limited, analysis, we tentatively consider that the ‘low-rate’ limit (-115dBm outdoor) is likely to be appropriate for the coverage estimation of unicast streamed audio services, and for comparison with DAB predictions.

It is important to note that this ‘low-rate’ threshold of -115dBm (outdoor) is considered a ‘legacy’ figure by Ofcom and is not necessarily valid in the original context of low-speed 4G data coverage. It is, however, a useful coincidence that it appears to be appropriate for estimating the edge-of-service for streamed audio services, as it allows us to re-use the Ofcom area and population coverage figures in the present context.

5 Network coverage prediction

5.1 Modelling options

The study specification required that a model be developed that forecasts mobile network coverage of data services (suitable for unicast delivery of radio content) over a 15 year timeframe. This model should take the current Ofcom 'Connected Nations' data as a starting point, and provide a similar breakdown of coverage under a variety of plausible scenarios.

The ultimate aim of the Working Group within the Review is to make explicit comparisons between the coverage afforded between FM, DAB and mobile networks, as well as between combinations of these. The ideal tool for this would be a series of matrix layers representing coverage by different networks and in different years across the whole county. These could then be logically or mathematically manipulated to visualise composite coverage or coverage differences.

A 'bottom up' approach to such modelling would involve the development of a comprehensive model of the radio access network (RAN) for each operator, taking into account topography, power levels, antenna patterns and network self-interference. Such an approach would duplicate that on which the Ofcom Connected Nations data is based. We have agreed that it would be inappropriate to attempt such an exercise in the present study. This is partly because the scale of the data gathering[22] and processing involved would be challenging in the short time available but, more fundamentally, because such detailed modelling would not be commensurate with the uncertainties that would necessarily attach to inputs such as future site locations, spectrum holdings, antenna performance, etc. To attempt such modelling would, therefore, only give a spurious impression of accuracy and detail.

We have, instead, adopted a strategic, scenario-based approach to modelling. This takes the 2019 Connected Nations data as a starting point, and provides year-by-year forecasts for network overall coverage. The forecast is implemented as a spreadsheet-based model. This model is based on known trends in network coverage in the UK (and where relevant elsewhere) and expected deployment events (such as the Shared Rural Network) to estimate the development of total nationwide coverage. The model necessarily makes some broad simplifying assumptions (such as the average coverage improvement per new site or from technology enhancements). As with any long term forecast it will also need to make assumptions on future network operator decisions which become increasingly uncertain on a longer timescale.

The coverage trends used in our modelling are known in terms of changes to geographic coverage. We have therefore taken geographic coverage prediction as the starting point of our modelling, and applied the same improvement profile over time to the cases of premises and roads coverage.

Broadcast coverage figures are often expressed in terms of population or premises coverage; our predictions are given as 'percentage-area' (for geographical coverage), 'percentage population' (for indoor coverage) and percentage-road-length (for road coverage).

[22] It is, for instance, implausible that MNOs would make the necessary detailed site data available to a third-party.

5.2 Factors affecting mobile network coverage

The model described below, which predicts the evolution of cellular coverage (in terms of land area, premises and roads) from the present to 2035, accounts for a large number of technical, regulatory and commercial factors. from other stakeholders.

These are summarised below, in approximate order of likely importance in determining coverage figures.

5.2.1 Shared Rural Network (SRN)

As described above, the 'partial not-spots' programme will act to substantially equalise coverage between operators. The total not-spots' programme (Scotland only) will extend coverage into areas that are not commercially viable to cover.

5.2.2 Extended Area Service (EAS)

This component of the Emergency Services Network, described above, is expected to extend coverage in remote areas of England, Scotland and Wales, adding around 1% of geographical UK coverage. This extension is dependant on commercial operators taking up the opportunity of adding equipment and providing services from the (Home Office funded) new masts.

5.2.3 Operator network expansion

The 'baseline' expansion that would be expected as a matter of course.

The MNOs are obliged to invest significantly in rural coverage as part of the SRN and so it is expected that the MNOs will prioritise remaining investment on capacity and densification in more profitable (populated) areas. However, some incremental improvements in 4G/5G coverage should arise from:

- Continued deployment of low frequency 4G spectrum (800 MHz)
- Re-farming of 2G and 3G spectrum to 4G (particularly 900 MHz low frequency spectrum)

5.2.4 Roll-out of MIMO antennas

MNOs are in the process of upgrading sites in urban and suburban areas to add 5G and to increase 4G capacity. As part of these upgrades, mid-band and, sometimes low-band, antennas are being upgraded to 4T4R[23] from the exiting 2T2R installations, which increases capacity by up to 70%. The 4T4R antennas also provide some improvement in effective coverage. Much of this coverage improvement will be in urban/suburban areas and to properties that are already predicted to have coverage but will now have better deep indoor coverage. It may though have some impact on overall population/premises covered.

5.2.5 Availability of 'new' spectrum

We do not consider that new frequencies will significantly improve geographical coverage. All MNOs have owned and deployed low frequency spectrum for several years now (most recently Three and EE with 800 MHz,

[23] i.e. four transmit and four receive antennas.

whereas O2 and Vodafone have had 900 MHz spectrum for many years). The upcoming 700 MHz spectrum can help to improve wide area capacity and edge-of-cell performance, but the calculated coverage area change is expected to be marginal. This will be validated and may be included in the model if significant.

Additional spectrum will provide the ability to support more capacity, and hence service performance, in urban/suburban areas.

5.2.6 Integrated car transceivers

Entertainment and navigation systems are increasingly integrated with automotive systems. This offers the possibility of significantly improved RF performance, if cellular transceivers have access to external antennas with large available aperture and excellent diversity and MIMO characteristics.

We would suggest liaison with the Radio Review Work Stream on 'Devices and Automotive' to understand possible options and time-frames for such development.

5.2.7 Technology and architecture improvements

Several advanced techniques for extracting increased performance from mobile radio networks may be deployed in the coming years. These include for example:

- Co-ordinated Multi-Point (CoMP)
  - Transmission or reception at multiple geographically separated sites to enhance system performance and end-user quality.
- 5G coverage enhancement features
- Self-Optimising Networks

Whilst these are valuable techniques for improving customer experience, and maximising capacity, we expect the benefits will be in currently-covered locations and will therefore not materially affect the predictions of future coverage.

5.2.8 4G vs 5G

High speed (i.e. excluding dedicated lower-speed Internet of Things (IoT) solutions such as LTE-M and NB-IoT) mobile coverage is primarily impacted by the frequency band and antenna technology deployed. The move from 4G to 5G does not in itself affect coverage. 5G in the UK currently uses higher frequency spectrum (at 3.4 GHz) than 4G which results in higher loses and therefore lower coverage area. This can be partially or fully compensated for by deploying higher order MIMO antennas including "Massive MIMO" antennas.

Over time we expect 3G and 4G low and mid-band spectrum to be re-farmed to 5G (using 'dynamic spectrum sharing' initially). However, this will not affect the forecast mobile coverage area.

The introduction of 5G, particularly with high-order MIMO antennas and additional spectrum, will enable capacity growth in urban areas. Also the anticipated standardisation of flexible multi-cast and broadcast capabilities on 5G will provide opportunities to scale multimedia services efficiently.

5.2.9 Power limits

The limit on power radiated from any base station is, ultimately, set by the need to comply with ICNIRP safety limits. In some European countries or municipalities, limits have been set substantially (10dB) lower than the ICNIRP values. If such an approach were to be adopted in the UK, it would be expected to have significant implications for coverage.

There is no suggestion, to our knowledge, that such a change is remotely likely in the UK. Equally, it is not plausible to consider that the present limits are likely to be relaxed, not least because of the febrile public debate around the issue of '5G safety'.

5.2.10 Planning rules

MNOs have calculated that significant coverage improvements, particularly in rural locations, would be possible by increasing the allowable height of masts. A regulation change allowing higher masts could improve long term coverage, especially road and geographic coverage, and would also make it cheaper to achieve SRN targets. Increasing mast heights on existing locations will though require MNO investments and so we expect this to be only selectively applied over a long period of time.

5.2.11 Infrastructure sharing & long-term consolidation

Increased infrastructure sharing, were it to happen, is most likely to focus on cost-saving rather than coverage improvement. As the SRN programme almost eliminates geographic partial not spots, any further impact of increased infrastructure sharing would have little impact on a geographic coverage measure, although it may improve premises/population and road coverage.

5.3 Coverage predictions

The model is a spreadsheet-based forecast of expected future coverage.

Coverage is modelled starting from Ofcom Connected Nations 2019 positions and using known programmes and activities to estimate future coverage percentages. Assumptions and approximations are made in order to forecast future coverage positions for which detailed MNO coverage analysis is not available.

There are three types of coverage in the Connected Nations report:

- 4G (high speed data and VoLTE)
- Lower speed data (2G, 3G, 4G)
- Voice (2G, 3G, 4G)

Our coverage model makes forecasts for the first two ('high-rate'' and 'Low rate') as data coverage is obviously a requirement for audio streaming. The 'Low rate' threshold should be sufficient for audio streaming to typical devices and is intended to be a median forecast, comparable with DAB predictions. The 'high-rate' case allows additional margin that should accommodate the worst-performing handsets and the more heavily-screened indoor reception cases, providing a more conservative forecast of customer experience of coverage. Appendix B gives more background on the choice of coverage threshold.

The 'Voice' coverage figure is a useful comparator as it uses the same RSRP threshold as 4G but currently has better coverage than 4G, which implies that not all sites have had their spectrum re-farmed to 4G from 2G or 3G. We expect all sites to re-farm spectrum to 4G over the next 5 years or so, and would therefore expect '4G' coverage to approach the same coverage as 'Voice'.

Coverage is forecast for 'All MNOs' (i.e. locations where all 4 MNOs have coverage) and 'Any MNO' (i.e. locations where at least one MNO has coverage). A customer of one MNO will experience only that MNO's coverage, which will always be somewhere between the 'All MNOs' and 'Any MNO' values.

As an observation, generally 'Any MNO' coverage is high, but 'All MNOs' coverage is significantly lower. This gap is expected to reduce over the next few years because of:

- The SRN Partial Not Spot programme (almost removing partial not spots)
- The continued deployment of low-frequency 800 MHz spectrum by EE and Three (O2 and Vodafone already have low frequency 900 MHz spectrum deployed on all their macro sites, as they have held that spectrum for many more years)
- The continued re-farming of the low-frequency 900 MHz band to 4G (from 2G and 3G) – this affects 4G data coverage, but not voice by O2 and Vodafone

5.3.1 Geographic coverage model

Outdoor geographic coverage forecasts, using the Ofcom '4G' or 'high-rate' coverage threshold, have been extensively modelled in the past year by MNOs as part of the SRN project. We can therefore be confident that the committed target points for 2024 and 2026 are accurate, assuming the SRN continues as planned. To forecast interim values, a typical deployment profile is assumed for each of PNS, TNS and EAS.

Our starting point is the 'Any MNO' UK coverage from the 'Connected Nations' 2019 Report; We make an adjustment of 1% to this figure due to expected, or already in-train, improvements prior to the start of the SRN programme. At the completion of the SRN, a geographic coverage of 95.0% of UK landmass is expected, with minimal further development, assuming the conservative 'high-rate' threshold.

Our tentative conclusion is that the 'low-rate' limit gives the most realistic estimate of coverage for streaming services. Predictions for this case use the appropriate Connected Nations figures as a starting point, and apply the same improvement profile. If the 'low-rate' threshold is assumed, the 'Any MNO' coverage increases to 98.5%.

Figure 5.1: Geographic coverage – any MNO (low-rate)

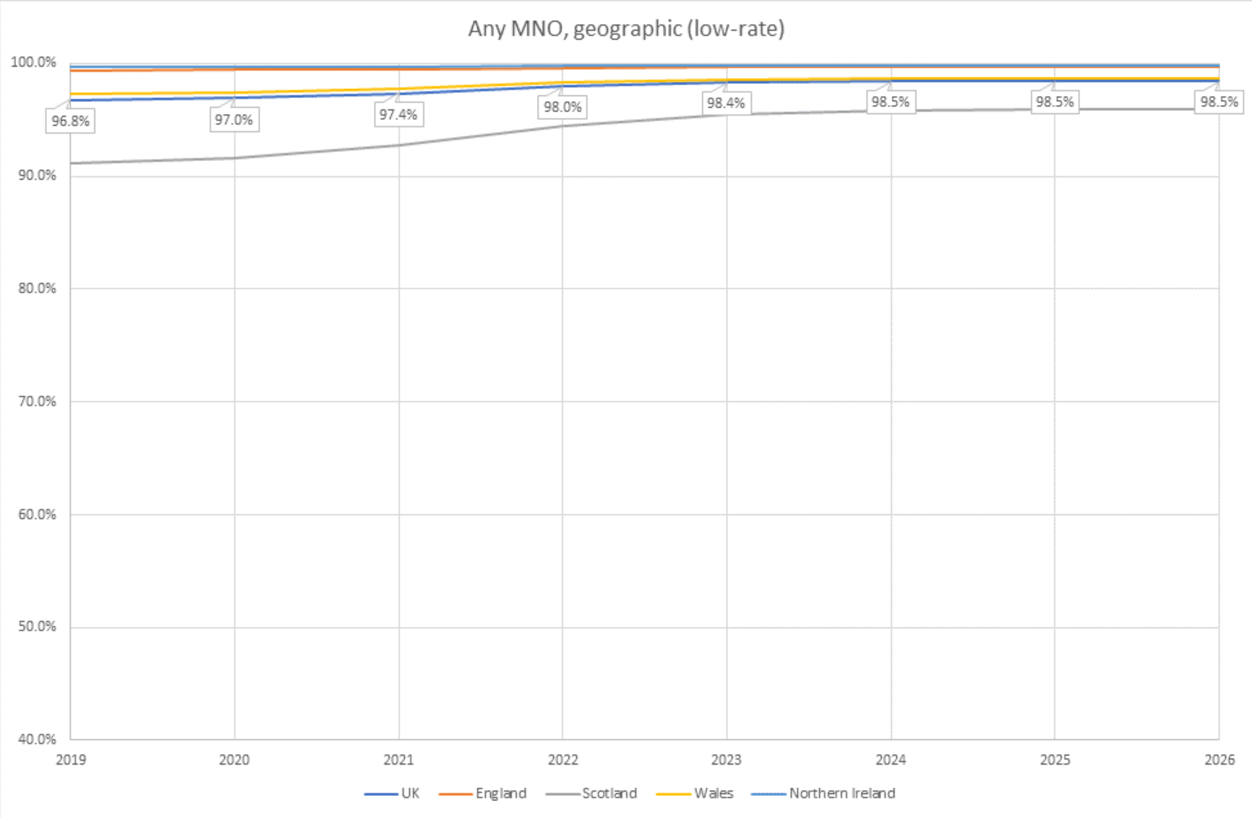
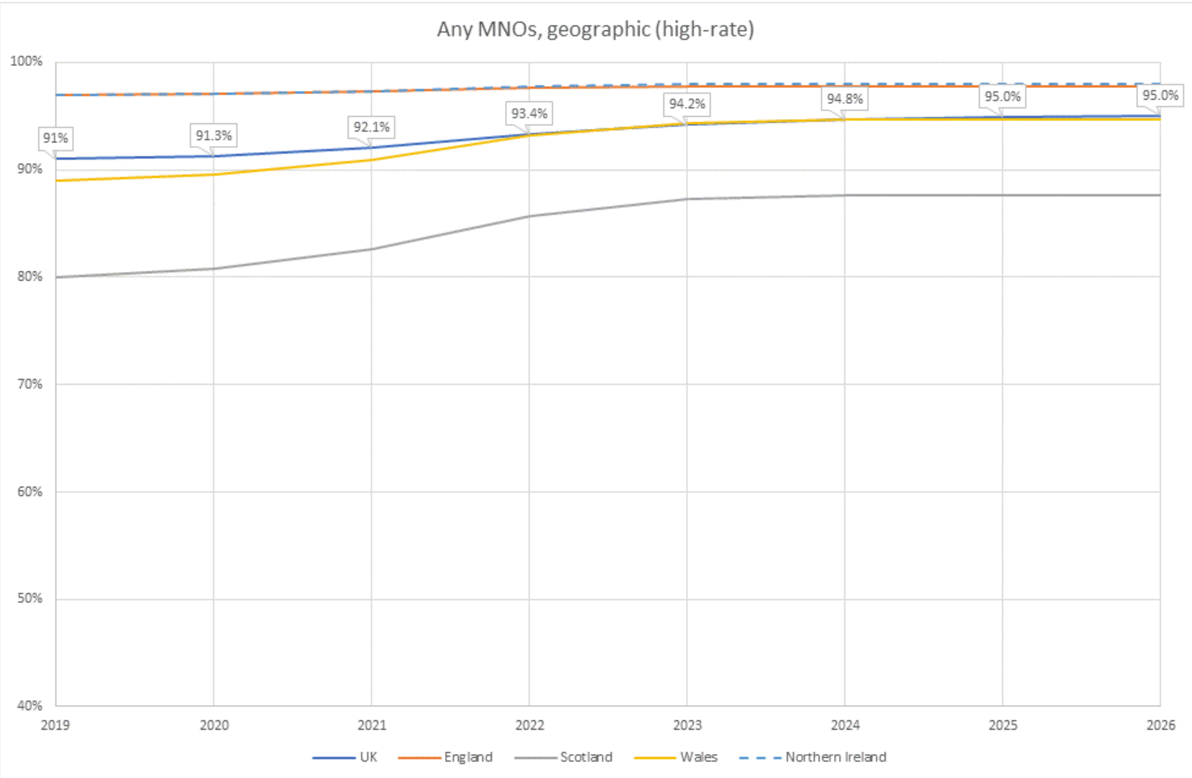


Figure 5.2: Geographic coverage – any MNO (high-rate)



The equivalent figures for 'All MNO' coverage are significantly smaller, despite the rapid equalisation that will occur as a result of the SRN programme, with an eventual UK coverage of 93%, or 84% for the high-rate threshold.

Figure 5.3: Geographic coverage – all MNOs (low-rate)

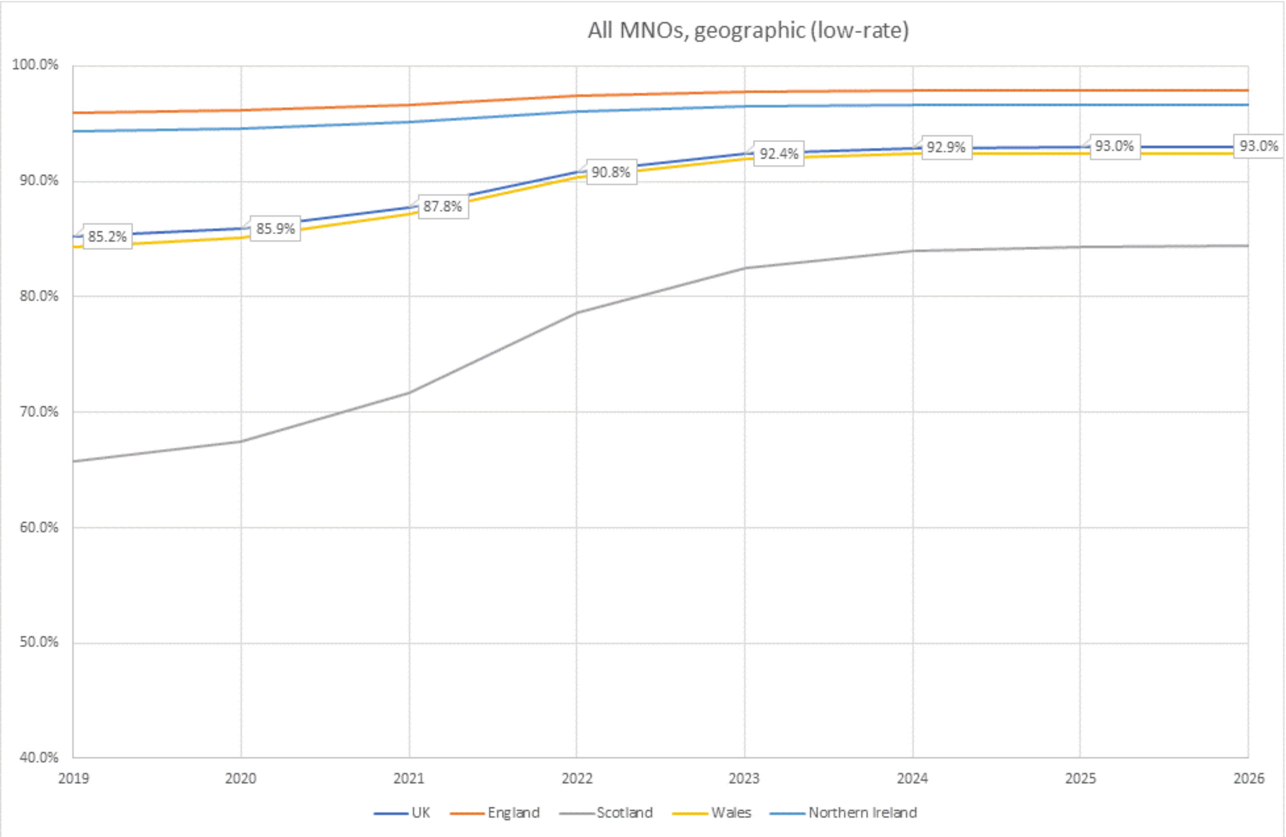
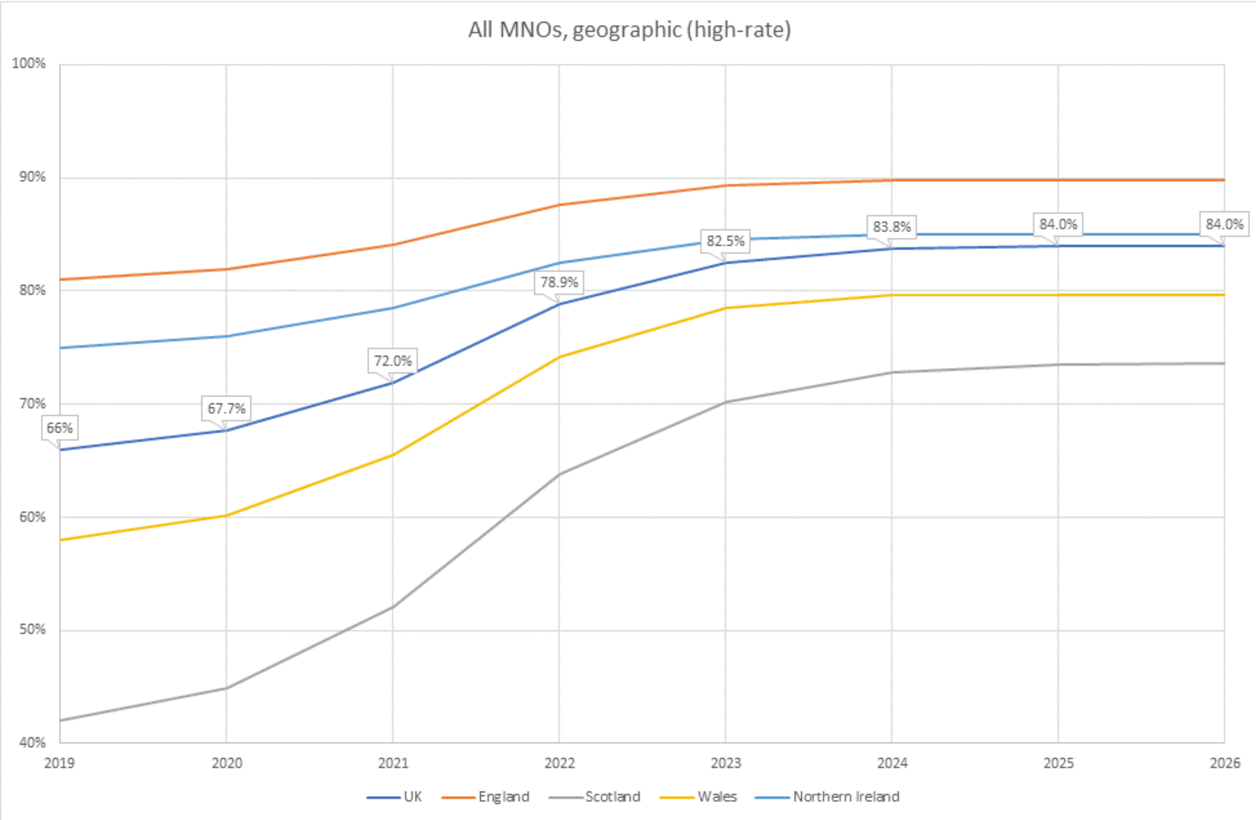


Figure 5.4: Geographic coverage – all MNOs (high-rate)



5.3.2 Indoor premises / population coverage model

For indoor population, the current best 4G (high-rate) coverage (O2) is 95%, which we take as a reference. We assume that all operators will approach that value over the next few years as Vodafone continues to re-farm low frequency spectrum to 4G and EE and Three make further deployments at 800 MHz and convert any remaining 3G sites to 4G; this is combined with the SRN PNS programme which will remove most partial not-spots. The SRN TNS programme will also add some population coverage (280,000 premises = 0.9%) to all operators. Therefore, we expect that every operator will reach around 97% indoor 4G coverage (at the 'high-rate'). The 'All MNO' figure will, necessarily, be lower than this, and is predicted to be 90.5%.

We assume that the trend for indoor premises coverage improvement will follow the same profile as that for geographic coverage improvement, which we believe reflects the likely timescales of all the known programmes. This profile is calculated as a proportional progress from the current coverage value towards 100% coverage (e.g. if current coverage is 50% and geographic coverage achieved progress 50% towards 100% then the new coverage would be 75%) and applied to the known starting positions for premises / population coverage.

The Ofcom 'Connected Nations' data also provides figures for 'lower speed' data coverage, which we tentatively consider to be appropriate as a coverage threshold for audio streaming services. This coverage level corresponds to a field strength 10dB lower than for the 'high-rate' case, and the coverage figures are correspondingly higher (indeed, 100% in all cases for the 'any MNO' case).

Figure 5.5: Indoor coverage – any MNO (low-rate)

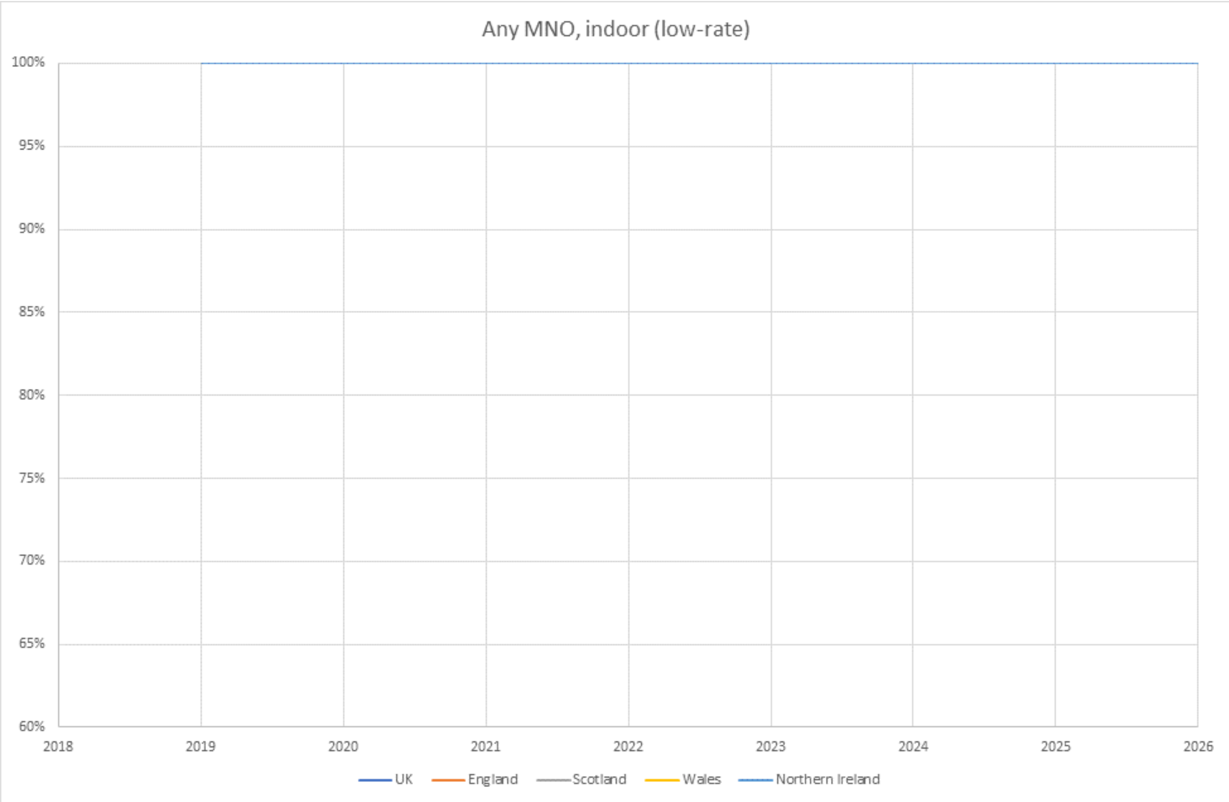
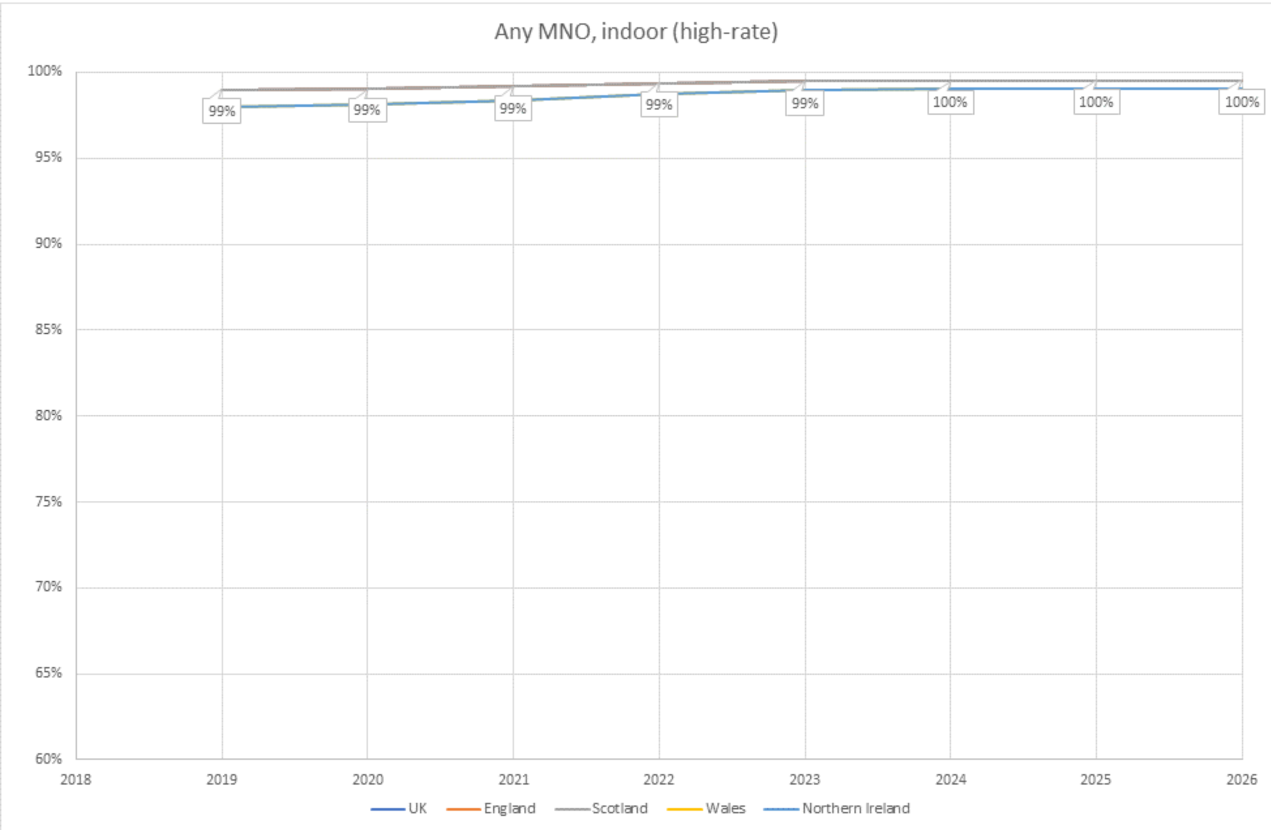


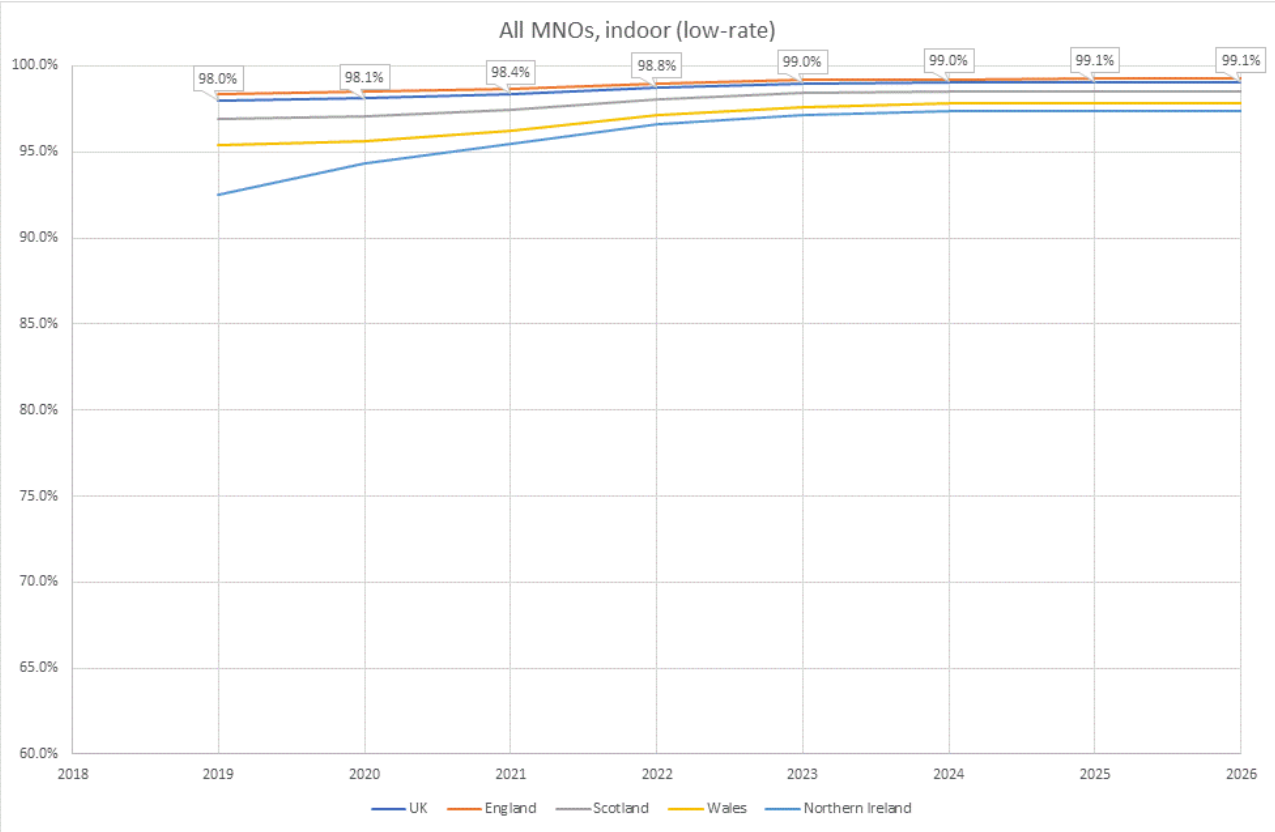
Figure 5.6: Indoor coverage – any MNO (high-rate)



When interpreting the coverage figures above, it should be borne in mind that the Ofcom threshold for indoor coverage that we have assumed does not guarantee ubiquitous indoor coverage, and a similar consideration applies to both FM and DAB predictions. In general we note that the uncertainties associate with estimating indoor coverage of DAB and cellular services are much greater than for the 'geographic' or 'roads' cases, due to the variation of building materials and structure and occasional high levels of indoor electrical noise. These issues are examined in more detail in Appendix B.

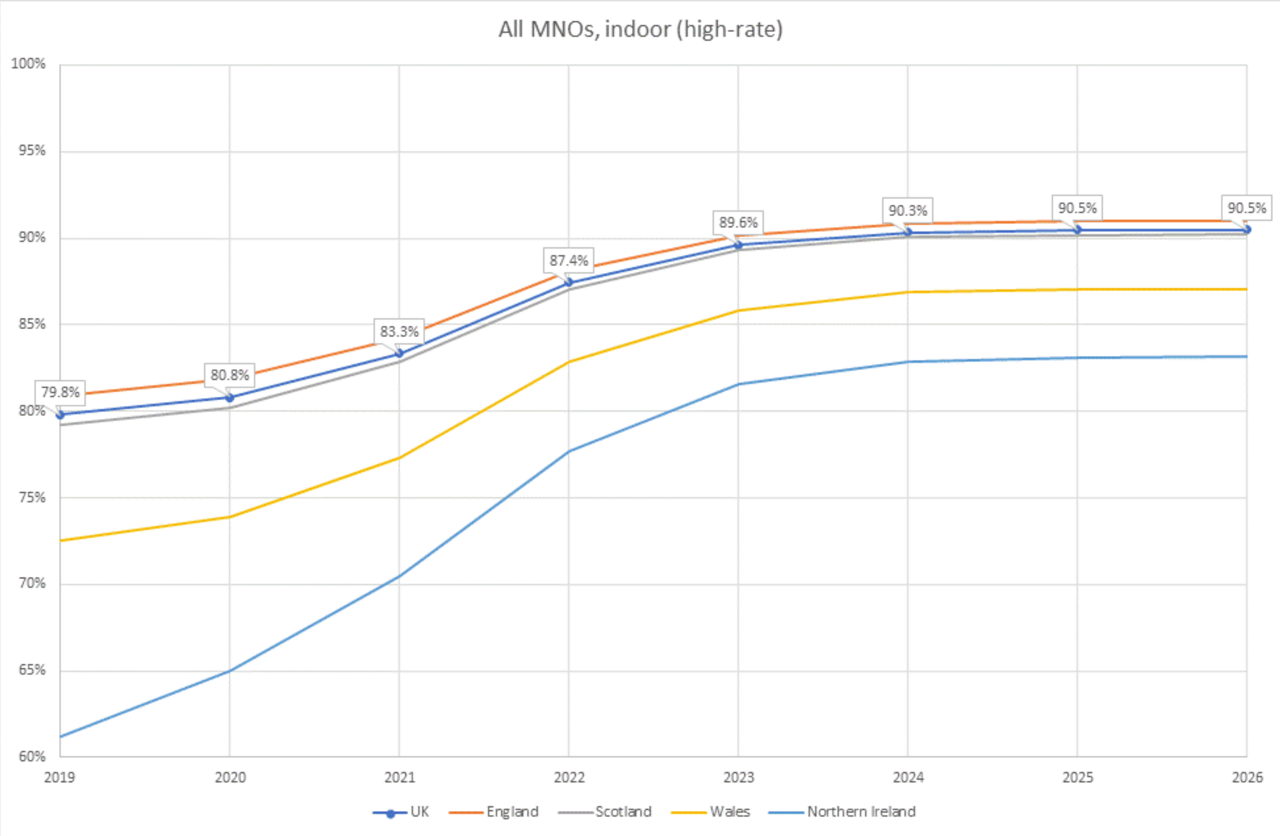
It should also be noted that 93% of households[24] (and increasing) have broadband with Wi-Fi and so, if using internet audio, a customer is likely to have Wi-Fi as well as mobile as options, improving the overall effective coverage over the mobile-only forecast.

Figure 5.7: Indoor coverage – all MNOs (low-rate)



[24] https://www.statista.com/statistics/275999/household-internet-penetration-in-great-britain/

Figure 5.8: Indoor coverage – all MNOs (high-rate)



We have also explicitly validated the end-point given by our model: If we assume two network footprints (MBNL and CTIL) each with 95% coverage and there is a 100% 'Any MNO' coverage, then the All MNO' coverage will be 95 + 95 – 100 = 90%. The SRN improvement profile used in the model takes the 'All MNO' end point to 90.5% which, allowing for small differences remaining between networks, appears to be a credible forecast.

If operators attain 97.5% each and 'Any MNO' high-rate coverage is close to 100% (which is a potential best outcome of all operator improvements including SRN TNS) this would give 97.5 + 97.5 – 100 = 95%. This gives a (perhaps optimistic) upside for the 'All MNO' 4G (i.e. 'high-rate') coverage.

Note that individual operators are what the customer will experience, unless roaming is used, and we expect in excess of 95% coverage for each individual operator at the high-rate.

5.3.3 Road coverage model

For road coverage we also assume the geographic coverage profile improvement, as we believe there is likely to be a good correlation between geographic coverage and road coverage. Coverage figures, which take the Ofcom data as a baseline, relate to A and B roads, and assume the use of an external antenna

The main difference between geographic and road coverage is that there is a considerable difference between operators. i.e. the 'All MNOs' coverage is rather low, and the 'Any MNO' coverage is rather high. This implies that different MNOs are covering different roads / sections of road and this could be a customer experience issue. We expect that the SRN PNS programme, together with further spectrum re-farming to 4G, will reduce, though not remove, the problem.

Figure 5.9: Road coverage – any MNO (low-rate)

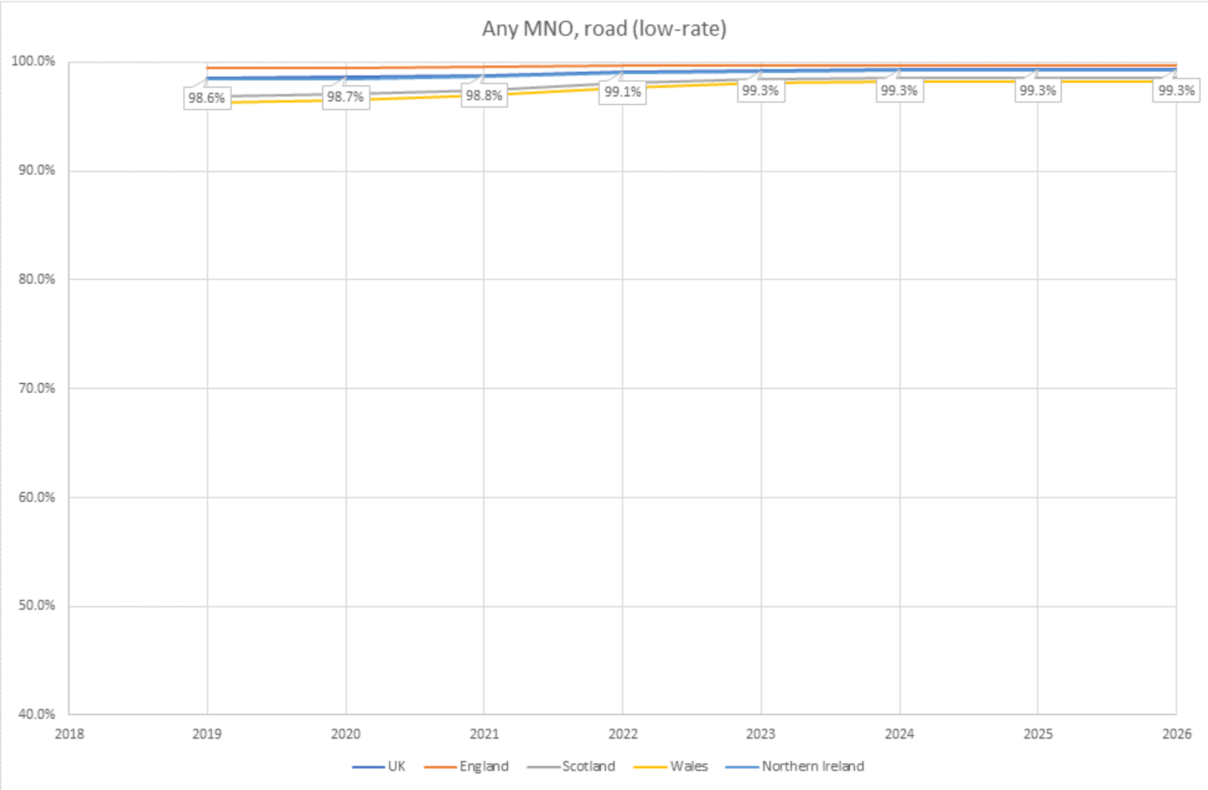


Figure 5.10: Road coverage – any MNO (high-rate)

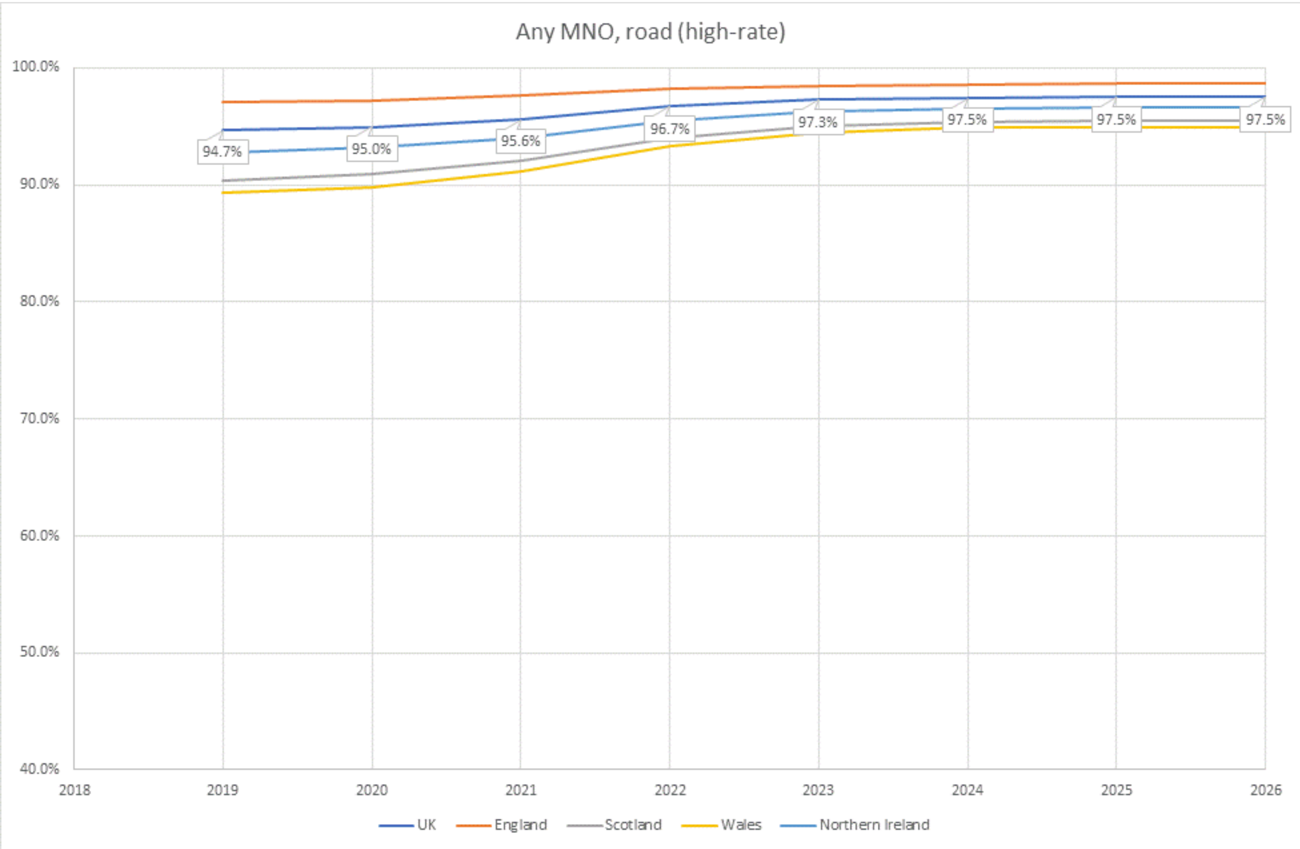


Figure 5.11: Road coverage – all MNOs (low-rate)

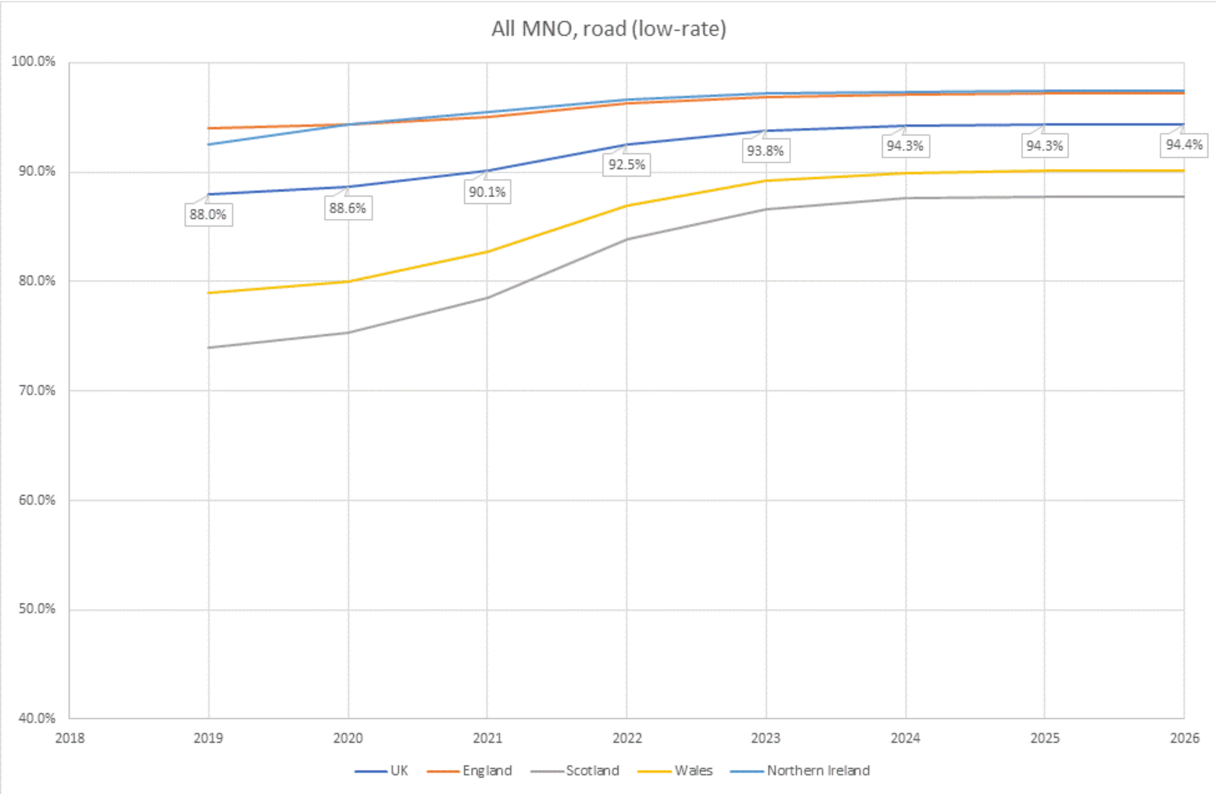
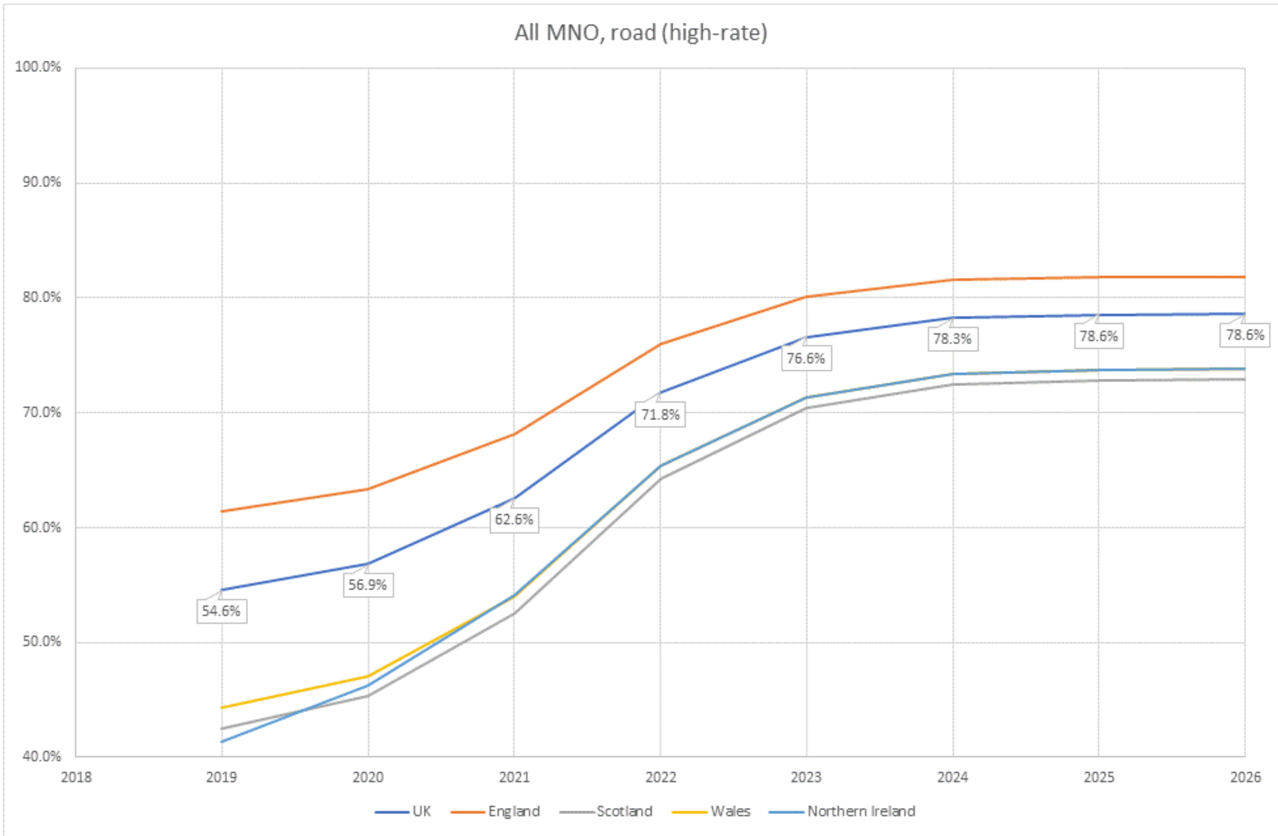


Figure 5.12: Road coverage – all MNOs (high-rate)



We have, again, validated the end point for the road coverage model. 'Any MNO' coverage is currently 94.7% for the UK at the 'high-rate' and SRN TNS will deliver an additional 16,000 km of road coverage (and a 1 million km total). This represents an extra 1.6%, taking 'any MNO' coverage to 95.3%. The model suggests a further improvement to 97.5% (or 99.3% for the 'low-rate' threshold) which appears reasonable given the SRN PNS programme and re-farming.

It is more difficult to validate the end-point for 'all MNO' coverage, so we are relying on a reasonable correlation with the geographic and population coverage improvements. With this assumption, all MNO road coverage attains a final value of 94.4% (78.6% for the low-rate criterion).

5.4 Summary

The chapter has presented predictions for 4G coverage suitable for the streaming of audio services; Unlike traditional broadcast networks, the availability of coverage is necessary, but not sufficient, as any network must also have sufficient capacity to carry the desired service. This is considered in the next section.

The table below summarises the predicted coverage figures for the 'low-rate' threshold, which we tentatively consider the most appropriate metric for unicast audio streaming. It should be noted that we consider the 'indoor' coverage figures to be the least robust as the proportion of coverage obtained in particular buildings is (inevitably) ill-defined.

Table 5.1: 4G audio streaming coverage ('low-rate' threshold)

Scenario		2019	2026
Geographic	Any MNO	96.8%	98.5%
	All MNOs	85.2%	93.0%
Indoor	Any MNO	100.0%	100.0%
	All MNOs	98.0%	99.1%
Roads	Any MNO	98.6%	99.3%
	All MNOs	88.0%	94.4%

The equivalent figures for the conservative 'high-rate' case are given in Table 5.2.

Table 5.2: 4G audio streaming coverage ('high-rate' threshold)

Scenario		2019	2026
Geographic	Any MNO	91.0%	95%
	All MNOs	66.0%	84%
Indoor	Any MNO	99.0%	100%
	All MNOs	79.8%	90.5%
Roads	Any MNO	94.7%	97.5%
	All MNOs	54.6%	78.6%

6 Unicast, multicast and broadcast delivery

6.1 Economic and commercial aspects

All current streamed content is delivered using unicast technology, establishing a one-to-one connection between the server and each users handset. Compared with broadcast or multicast delivery, this may appear inefficient, but given that it is, generally, unlikely that many users in a single cell will be demanding the same content it is unlikely to represent a significant overhead. There may be some exceptions to this, for instance at sports stadia or festival venues, with a high density of users with a common interest.

One of the issues with early multicast implementations (e.g. eMBMS) were that they did not allow for non-subscriber access but this was addressed in 3GPP Release 14 which allows delivery of free-to-air content to devices without SIM cards or service subscription. The recently frozen Release 16 provides further radio access enhancements including more a flexible cyclic prefix to allow either high-speed operation or greater inter-site distances with 'LTE-5G terrestrial broadcast'. Release 17 will add support for 5G NR multicast and broadcast support but the features are primarily for small scale and single-cell deployments and not large scale SFNs or receive-only devices. The EBU has published a recent technical report[25] which summarises these developments.

There appear to be a number of factors for the limited traction around eMBMS/LTE-Broadcast.

- First, the device ecosystem is limited; according to GSA's GAMBoD database[26] there were, in September 2020, only 46 devices support this feature, of which only 5 are phones (the others being fixed terminals, routers or USB modems).

- Second, there is little economic incentive under the conventional business model of MNOs (based on selling data packages) to deploy eMBMS on a large scale. Outside congested hotspots, there is little need for eMBMS to improve spectral efficiency (there are also other alternatives such as spectrum re-farming which make more sense from the network planning perspective). Only a handful of operators (Telstra, China Unicom, Reliance, KT, Verizon) have launched eMBMS[27]. Given the lower bandwidth requirements for radio streaming (~40MB for an hour of radio/music streaming) compared to video (~1GB for 1 hour), it would seem that the case for eMBMS/LTE-B to support radio streaming is even harder to justify.

- Thirdly, while the sim-free idea is possible conceptually there has already been significant resistance from incumbent operators to soft SIMs, so this may be unlikely to happen in the short to medium term.

On commercial aspects, broadcasters would be free to enter into specific service level agreements (SLAs) with MNOs although public service broadcasters might be obliged to do so with all MNOs (and possibly MVNOs) so that the guaranteed same service quality is accessible for all users across different mobile networks.

Another common strategy is zero-rating (the practice of excluding some traffic, such as that associated with music streaming services, from data caps[28]). These are usually commercially negotiated between MNOs and content providers. For public service broadcasters such arrangements might be controversial particularly if they raise competition concerns (between MNOs and between competing radio providers). It is noted that all four MNOs zero-rated NHS websites during the COVID-19 crisis[29].

[25] https://tech.ebu.ch/publications/tr054
[26] https://gsacom.com/gambod/
[27] https://gsacom.com/paper/lte-broadcast-embms-market-update-july-2019/
[28] https://www.o2.co.uk/termsandconditions/mobile/music-streaming-inclusive-on-selected-tariffs-terms-and-conditions
[29] https://mobilenewscwp.co.uk/News/article/operators-offer-free-access-nhs-sites

6.2 Mobile versus broadcast networks – transition issues

The primary concern of this report is to estimate the coverage available from cellular networks when used for the wireless delivery of audio services,. There are a number of other aspects that need to be considered when assessing the likely user-experience, and perceived differences between mobile networks and broadcast networks.

- Capacity: In broadcast networks capacity is dedicated to each broadcast channel. In mobile networks capacity is shared amongst all users of a cell, typically using a 'weighted fair-scheduling' algorithm[30]. This means that in mobile networks an audio service could be adversely affected by congestion in busy locations due to other traffic being carried by the cell, or by congestion elsewhere in the mobile network. If a site becomes congested (i.e. more demand than the capacity of the site) the main issue is not the detail of the scheduling algorithm, but that the available speed per device will be limited and eventually drop below that required for consistent audio streaming. A mechanism for prioritising quality of service (QoS) would enable audio streaming services to take priority in the scheduling over other services, improving the chances of having sufficient speed to support the service.

- Mobility and handovers: Mobile networks consist of thousands of cell sites and so devices (e.g. handsets) on the network are frequently changing connections to different cells. These handovers between cells are handled effectively by the mobile network and are typically invisible to end users with no interruption to service, and so do not constitute a problem for audio services. However, devices can also connect to Wi-Fi network. Handovers between mobile networks and Wi-Fi networks (and particularly handovers in the opposite direction - Wi-Fi to Mobile) are generally not handled well and can lead to interruptions of service. Also, Wi-Fi networks themselves may have capacity or coverage issues.

- Wi-Fi quality: Most mobile devices are configured to connect to Wi-Fi in the home and in locations out and about where there are Wi-Fi services. The quality of the Wi-Fi service and the potential congestion is outside the control of mobile operators, but will have a substantial impact on customer experience if there is insufficient performance to support reliable audio services.

6.2.1 Capacity

The bandwidth required for audio services is relatively small compared to the capacity provided by 4G and 5G cellular networks and compared to other services such as video streaming. This makes it feasible to treat some audio services as VIP services and provide prioritisation over other cellular traffic.

a) Quality of Service (QoS)

A mobile network might implement QoS mechanisms to prioritise the audio services over other "best effort" services. This is the mechanism being used for the Emergency Services Network (ESN) where emergency services calls and data are prioritised above all other traffic on the network; similar methods are used to implement 'Voice over LTE (VoLTE) services. Audio streaming services could be marked as a higher priority than standard traffic on the network, hence providing resilience from congestion (particularly important in busy urban and high footfall locations).

b) 5G network slicing

[30] This is a method of scheduling radio resources that balances between performance for devices that are in poorer coverage conditions and overall cell capacity that would favour assigning more resources to devices in better coverage (enabling higher order modulation and hence more throughput per Hz of spectrum).

5G provides a mechanism for reserving a logical slice of the mobile network for services that require specific performance characteristics. This is probably overly complicated for audio streaming services that are not particularly demanding on performance but is an option for the future to further guarantee performance.

c) Multicast / Broadcast

As noted above, in some locations where there are expected to be many simultaneous listeners to the same audio stream it could be more economic to implement a multicast / broadcast service rather than the usual unicast service, i.e. where each user gets their own dedicated audio stream, hence ten simultaneous listeners would generate ten times the traffic of one user. A multicast/broadcast solution would only transmit one stream in the cell that would be received by all listeners.

4G and 5G define mechanisms to provide multicast and broadcast delivery but, to date, they have not been implemented for a range of reasons - chiefly because there has been no convincing business case to implement them. Very few events and locations have generated sufficient simultaneous viewing or listening to warrant the expense and complexity of implementation. Also, implementation requires devices to support the multicast / broadcast mechanism and since operators have not had the business case, the device/handset vendors have not been pushed to provide solutions.

It is possible that the more flexible solution in 5G may enable multicast and broadcast to finally be implemented on mobile networks and in devices/handsets. However, it is likely still to need a clearer business case and more operator (or their customers) drive.

6.2.2 Mobility and handovers

a) Mobile to Mobile handovers

Mobile-to-mobile handovers are already highly performant and invisible to services running on top and so do not require further work

b) Mobile / Wi-Fi handovers

Typically, a mobile handset, when connected to Wi-Fi, will hold on to Wi-Fi coverage for too long after the quality of connection has degraded, this can lead to interruptions to the data service and hence audio streaming services. Each device can implement and configure this differently and so perform differently.

One solution that helps with this problem is Multipath TCP. If an application is built with support for Multipath TCP and the handset/device also supports this, it can reduce the interruption time or potentially eliminate it. Multipath TCP works by sending and receiving data over two different connections at the same time (i.e. the mobile network connection and the Wi-Fi connection); so that when the Wi-Fi signal degrades the traffic can start to flow on the mobile network, rather than waiting for the device to switch primary connection.

There is a potentially negative consequence for operators in that more traffic may flow on the mobile traffic and less on the Wi-Fi compared to a typical Wi-Fi-preferred configuration. However, devices can configure this independently from the operator (unless the operator has agreed with the device vendor an operator-specific configuration to disable the feature).

It is recommended that MP-TCP be considered for future audio streaming services apps on devices/handsets.

6.2.3 Wi-Fi quality

This is a difficult problem to solve as there are so many Wi-Fi hotspots and many different providers it would be virtually impossible to guarantee performance on all Wi-Fi connections. Implementing the latest Wi-Fi hotspot standards could help with connectivity reliability. Avoiding splash pages (that interrupt the connection to force a human interaction in order to continue) will also help. Implementing MP-TCP for the audio streaming applications will also reduce dependency on the Wi-Fi quality somewhat.

To some extent customers can self-select to disable Wi-Fi connection to regularly poor performing hotspots. Also, somewhat speculatively, prioritising mobile over Wi-Fi may become more common as advanced 4G and 5G gets more widely deployed.

7 Conclusions and further work

7.1 Conclusions

Mobile coverage is already broadly comparable with DAB for geography, premises, and road. For consistent customer experience it is important that all operators provide similar coverage (i.e. minimising partial not spots), and this is currently being addressed through the Partial Not-Spots element of the Shared rural Network programme (SRN).

The next 6 years will see a significant improvement in mobile coverage, particularly in terms of geographical coverage in rural locations, largely due to the SRN.

Mobile coverage of premises is already nominally close to 100% (when using the low-rate data threshold, tentatively identified as appropriate for audio services) and will also improve over the next 6 years. The statistical definition of 'indoor coverage', for both DAB and cellular services may, however, not be robust (see below). When combined with Wi-Fi in home (with broadband expansion programmes in progress) it is expected there will be near universal availability of IP services to the home.

Road coverage will also improve, but gaps in coverage will remain and this is an area that may require further attention (e.g. a combination of network operator deployments and vehicle manufacturer external antennas for in-car systems)

7.2 Suggestions for further study

As noted elsewhere in this report and the annexes, the coverage of services delivered over broadcast or mobile networks can only be assessed in statistical terms.

This is true of traditional broadcast delivery, but even more so for cellular services, where there are many more variables involved, most of then not under the control of broadcasters. Undertaking a formal technical investigation of the statistical nature of streaming coverage thresholds is strongly recommended. This should incorporate calibrated measurements of 4G or 5G received signal strength in typical environments, in parallel with the logging of streamed audio, ideally including information on buffer state. Both Ofcom and Arqiva have undertaken some work along these lines, though the Ofcom work considered general data services rather than streaming.

In parallel, it is also important to understand the variability of handset performance, and the implementation details of the different streaming applications. Considerable work has already been done on the former issue (see Appendix B), but it would be useful to re-interpret this data in conjunction with the threshold measurement work. During this study, attempts have been made to understand the architecture of the various streaming applications, but the relevant information has not been readily accessible in the limited time available. It would be valuable to initiate a dialogue with the relevant software developers to explore the extent to which the specific characteristics of 4G and 5G radio channels are allowed for.

Some work to quantify the advantage that might be expected from the (wider) adoption of integrated cellular antenna systems in vehicles would be useful, to understand the improvement in coverage that might be expected with respect to the current use of smartphones within vehicles.

The present, brief, study has focussed on estimating geographical coverage of services. As noted in the report, quality of service may be degraded by network congestion issues; the severity of such degradation is hard to assess in general terms depending as it does on the detail of local traffic and individual network configuration. Simulation, and especially measurement, of the impact of network congestion in busy urban areas and heavy traffic would be very desirable.

Finally, if the results of the present work are to be usefully aligned with the coverage predictions being produced for FM and DAB services, a detailed dialogue regarding assumptions of availability and reliability would be valuable. This is particularly the case when considering indoor coverage of both DAB and 4G services.

7.3 Suggestions for issues to be addressed by the industry

We have identified a number of issues that may require pro-active work by industry to ensure that cellular delivery of radio services provides the best possible consumer experience.

7.3.1 Multipath TCP (MPTCP)

Promote the use of MPTCP on audio streaming applications, devices, and servers to enable a seamless Mobile – Wi-Fi handover experience.

7.3.2 QoS prioritisation

Mobile networks can mark IP data from particular services as higher priority in order to guarantee quality of service (QoS). Unlike broadcast networks, mobile network can suffer from congestion as they use shared capacity across all data services. To ensure audio broadcast services do not degrade on busy mobile sites and busy times, it is recommended to implement QoS mechanisms. This would prioritise the audio services over other services in situations where this is a significant amount of congestion. QoS prioritisation is suitable for the relatively low bit rate used by audio streaming services. Issues to be considered are net neutrality (where operator are not allowed to favour one particular commercial organisation over another in delivering internet traffic), technical implementation and commercial arrangements between operators and broadcasters.

7.3.3 Multicast/broadcast

In locations with extremely large numbers of users, all watching the same live audio streams, it may be more efficient to implement a multicast/broadcast mechanism on the mobile network, rather than using individual replicated unicast streams. To date there has not been sufficient evidence of locations where this would be beneficial versus the cost of implementation. However, the 5G standards provide a flexible method which may open opportunities for the future, and manufacturers should be encouraged to further develop and implement multicast functionality.

7.3.4 In-vehicle solutions

Solutions for providing more reliable in-vehicle audio streaming services might be considered. There are currently two main ways for providing IP wireless audio streaming services to vehicles:

- Connected-car solutions, where the manufacturer-provided in-car entertainment system has an embedded SIM and an external antenna to connect to the mobile network. This has advantages of better antenna gain than handsets and potentially (but not commonly) the ability to have multiple SIMs enabling roaming between networks for best coverage availability.

- Smartphone connected via Bluetooth to the car (e.g. Bluetooth audio, Apple CarPlay, Android Auto). Benefits are convenience and in the case of Apple and Android a sophisticated user interface that provides access to many applications. However, coverage will be worse due to using a lower gain handset antenna that is also inside the car.

Appendix A Glossary

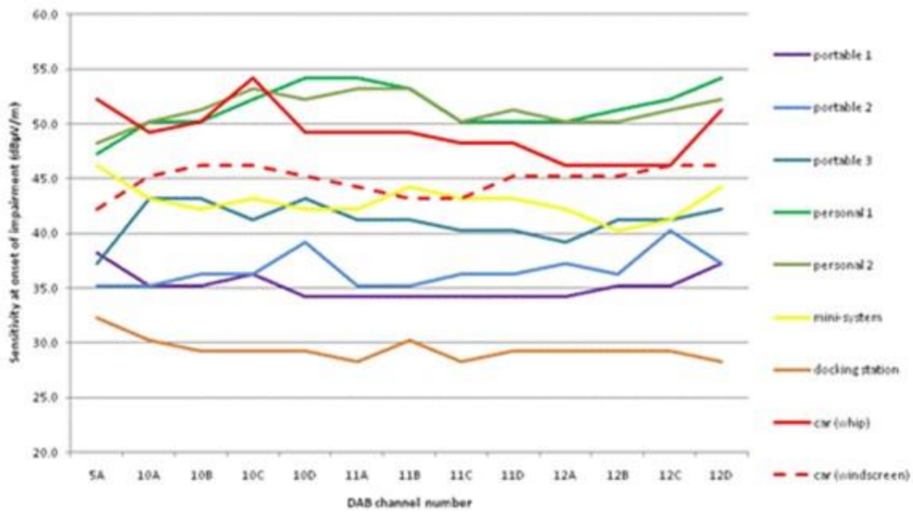
3GPP	'Third Generation Partnership Project'. The standards body initially charged with developing 3G, then 4G and 5G standards.
CEPT	*Conférence Européenne des administrations des Postes et des Télécommunications*. The co-ordinating body for European state telecommunications organisations.
CTIL	Cornerstone Telecommunications Infrastructure Limited. A site-sharing joint venture between Vodafone and O2.
DAB	Digital Audio Broadcasting. Specifically the European Eureka 147 standard.
DCMS	Department of Culture Media and Sport (UK Government)
DMSL	Digital Mobile Spectrum Limited, a company jointly-owned by the UK MNOs. Originally established to manage the mitigation of interference to digital TV following the 800 MHz clearance, it is now the body charged with administering the TNS elements of the SRN.
EAS	Extended Area Service: Sites being built in England, Scotland and Wales by the Home Office for the Emergency Services Network (ESN) programme and adding around 1% UK geographic coverage.
eMBMS	Evolved Multimedia Broadcast Multicast Services
FeMBMS	Further Evolved Multimedia Broadcast Multicast Services
FM	Frequency Modulation. Here refers to VHF sound broadcasting in the 87.5-108.0 MHz band
GSA	The Global Mobile Suppliers Association; an industry organisation representing companies supplying mobile infrastructure, test equipment, devices and applications.
GSM	The European standard for 2G, developed by the 'Groupe Speciale Mobile' of the CEPT (q.v.)
IoT	The 'Internet of Things', where very large numbers of low-cost sensors, control devices, etc are connected over (generally) low-bitrate links.
LTE	'Long Term Evolution'. The set of technical standards used to deliver 4G services and defined by the 3GPP (q.v.)
LTE-M	Part of the 4G standard set targeted at IoT applications.
MBNL	Mobile Broadband Network Limited. A site-sharing joint venture between EE and Three.
MIMO	Multiple Input Multiple Output (of antenna and coding technique)
MNO	Mobile Network Operator. Only physical network operators (Vodafone, O2, Three, EE) are considered here, not 'virtual MNOs' who buy capacity on those networks.

MPTCP	Multi Path TCP. Allows a TCP (q.v.) connection to use multiple paths to increase redundancy and improve quality of service.
NB-IoT	Part of the 5G standard set targeted at IoT applications.
NR	'New Radio' The set of technical standards used to by 5G radio networks and defined by the 3GPP (q.v.)
OFDMA	Orthogonal frequency Division Multiple Access. Technique used in LTE and NR (q.v.). DAB uses very similar techniques.
PNS	Partial not spot. An area where mobile service is not provided by all MNOs
SFN	Single Frequency Network
SRN	Shared Rural Network. Joint venture between MNOs and the Government to improve 4G coverage.
TCP	Transmission Control Protocol. A fundamental protocol for internet traffic, allowing reliable connection-based data transport (unlike, for instance, UDP).
TETRA	Trans-European (or Terrestrial) Tunked Radio. A digital standard for professional mobile radio developed in the 1990s.Typically operating at frequencies around 400 MHz, only low-rate date (up to a few hundred kbit/s at most) is supported.
TNS	Total Not Spot. An area where mobile service is not provided by any MNO
UDP	User Datagram Profile. An internet 'best-effort' protocol that sacrifices reliability in favour of speed and low-latency.
UMTS	The set of technical standards used to deliver 3G services and defined by the 3GPP (q.v.)
VOLTE	'Voice over LTE'. The initial release of LTE did not include the option for voice calls, so networks relied on 2G and 3G connectivity to provide this. VOLTE was added later to allow stand-alone 4G voice calls.

Appendix B Technical coverage criteria

In traditional broadcast planning, coverage is defined in terms of field strength (dBµV/m), often at a standard height of 10m above ground. Field strength limits are then chosen on the basis of the expected performance of the majority of receiver antennas[31], although in practice these will show a very wide distribution, as seen in Figure B.1.

Figure B.1: Measured DAB receiver sensitivity figures (Plum)



Cellular coverage criteria, by contrast, are expressed in terms of the absolute power (dBm) measured at the user equipment antenna port, and must therefore include some assumptions regarding the gain of typical antennas. These have been shown[32] to vary widely between devices, and will also change systematically with frequency. The assumption regarding gain should be stated in both cases, and should be appropriate for the application.

B.1 Building entry loss

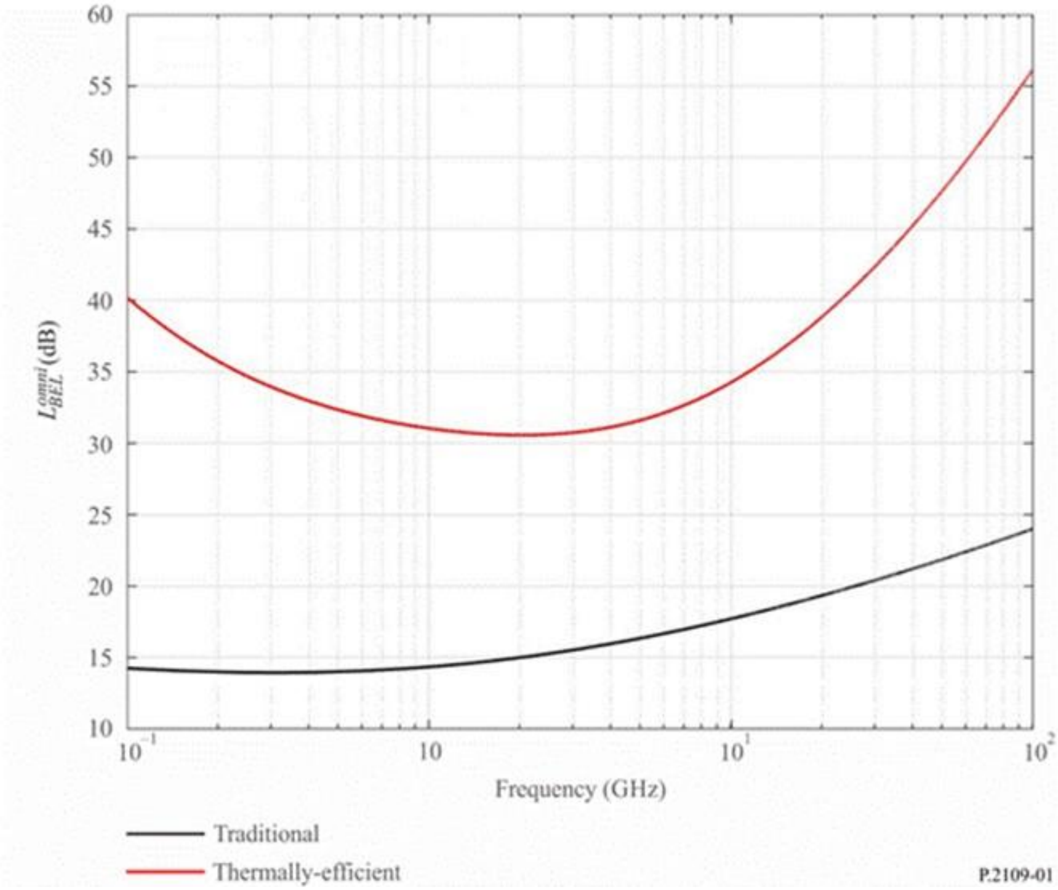
Plum have undertaken a substantial amount of work[33] on the topic of building entry loss in recent years, and this work has informed the current ITU-R Recommendation, ITU-R P.2109, on the topic.

This work, and that of may others within the framework of ITU-R Study Group 3 served to highlight the enormous variability of building loss. A particularly large difference in loss was found between buildings of traditional construction and those where attention had been paid to thermal insulation, through the use of metallised materials such as sputtered glass and foil-backed plasterboard. The gulf between the two categories led to separate models being developed.

The ITU curves for median building loss are reproduced below.

[31] Examples of DAB car antenna performance are given in Annex C of EBU Tech 3391 (https://tech.ebu.ch/docs/tech/tech3391.pdf)
[32] ComReg, the Irish regulator publish an extensive set of measurements at file:///C:/Users/Richard/AppData/Local/Packages/Microsoft.MicrosoftEdge_8wekyb3d8bbwe/TempState/Downloads/ComReg-1882%20(1).pdf
[33] E.g. https://www.ofcom.org.uk/__data/assets/pdf_file/0016/84022/building_materials_and_propagation.pdf (undertaken by now merged with Plum).

Figure B.2: Median building loss (ITU-R Recommendation P.2109)

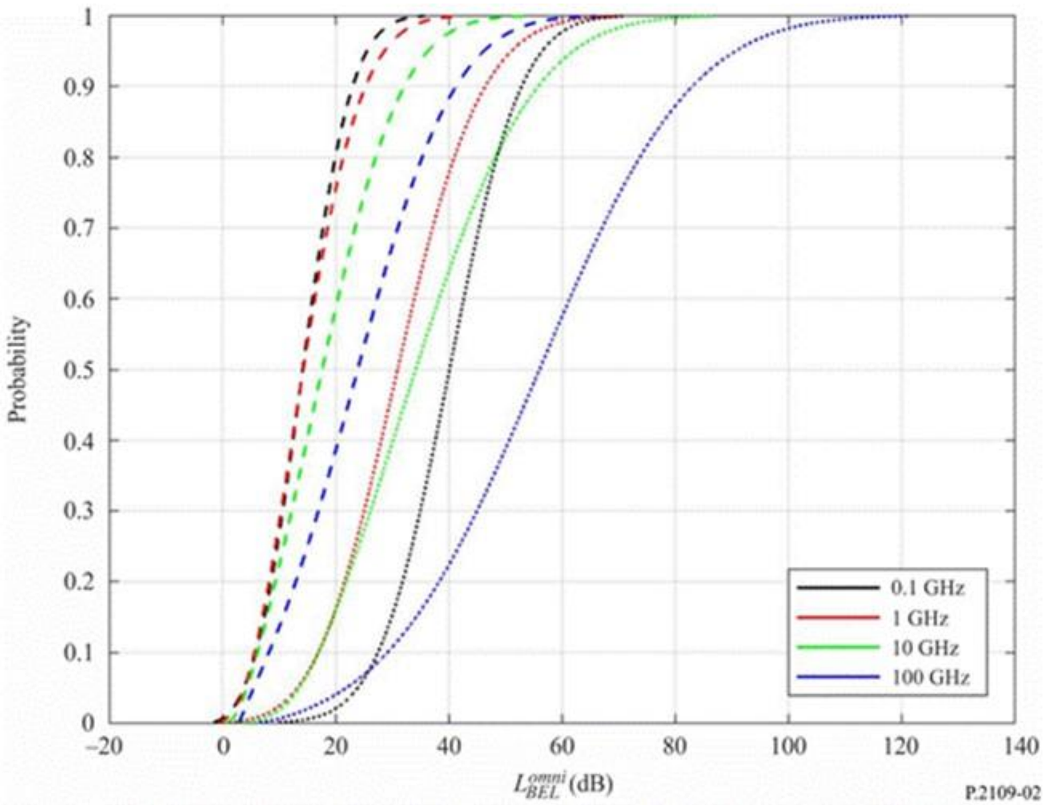


An interesting feature of this model, which is based on some 40 sets of measurement data from around the world, is that there is a non-monotonic trend of loss with frequency, particularly for the 'thermally-efficient' case. It can be seen that predicted building loss rather smaller at cellular frequencies from around 1-3 GHz that at 100 MHz (FM) or 200 MHz (DAB). Nevertheless, the overall losses in such buildings are generally so high as to present coverage problems for any radio system.

For radio listening, the statistics for traditional buildings are more likely to be relevant, and here the median loss is around 14dB for both FM and DAB, and also for the lower cellular bands at 700MHz, 800MHz and 900MHz. The often-made assumption that these higher frequencies suffer greater building loss than traditional broadcast bands was not supported by measurement. The frequencies around 3.5 GHz currently being used for the roll-out of 5G services, however, do suffer median losses several dB higher.

For the system planner, the variability of building loss is as important as the median value. The problem here is that to predict loss in the tail of the distribution, for example to ensure coverage of 90% or 95% of the building, implies a very large number of measurements in a wide range of representative buildings. Although the database of results is growing, the statistics are necessarily uncertain, given the enormous variation in building types. The figure below shows the current estimate of the fading distribution within the generality of buildings.

Figure B.3: The variability of building loss (ITU-R Recommendation P.2109)



These curves suggest that for traditional buildings (dashed curves), to ensure 80% building coverage at FM, DAB or 800 MHz cellular frequencies would require a margin of around 20dB with respect to the outdoor threshold.

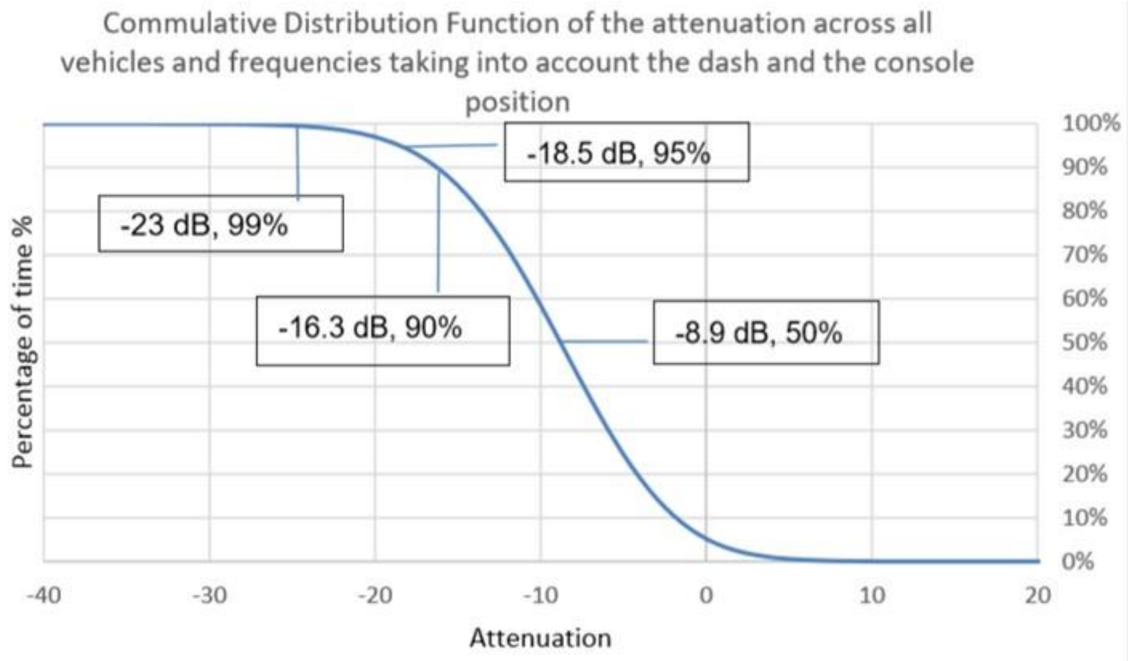
It is relevant to note that the 10dB margin for building loss assumed by Ofcom in the Connected Nations report (and often in published data by the MNOs and other bodies) would only ensure coverage in some 30% of a typical 'traditional' building. In practice, of course, this may be a satisfactory value bearing in mind (i) that the 30% would only apply in buildings near the edge of coverage and (ii) that listeners may well cooperate in positioning traditional radios in locations where reception is known to be reliable (e.g. kitchen windowsills).

The variability seen in building loss makes it crucial that assumptions are aligned in any comparison between the coverage of different networks.

B.2 Vehicle Entry Loss

In the Connected Nations report, a blanket figure of 10dB is assumed for vehicle entry loss. Our informal observations, in the course of the work described in Appendix C, are that signals received by a phone on the dashboard, deliberately positioned in as unobstructed a location as possible, were around 5dB lower than outside the car.

Figure B.4: Vehicle entry losses (LS Telcom report for Ofcom[28])



A 2017 study[34] by LS Telcom for Ofcom found that median losses to in-car devices were 8.9dB, with 90% of all measurements showing a loss less than 16.3dB.

B.3 4G cellular coverage thresholds

The highest bitrate used[35] in coding BBC radio content is 320kbit/s, although most smartphones are currently likely to be using lower rates. At present, access to such services will be via unicast delivery.

As has been noted in the body of the report, the differences between the physical layer of 4G (LTE) and 5G (NR) are relatively minor in the context of the wide-area coverage of relatively low-rate services.

B.3.1 LTE and NR physical Layer

This outline description of the LTE physical layer is included to provide background to the use of the RSRP criterion for coverage.

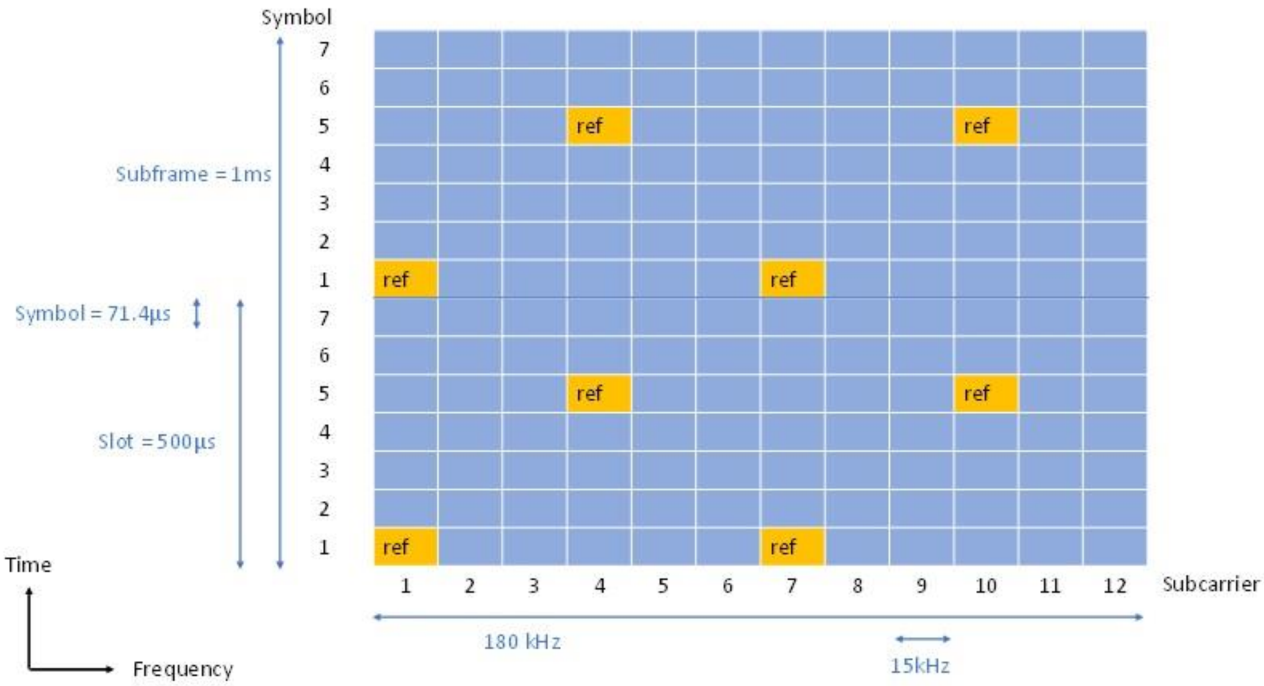
The LTE downlink uses Orthogonal Frequency Division Multiple Access (OFDMA), with a subcarrier spacing of 15 kHz and a useful symbol time of 66.7µs. The cyclic prefix (CP) is normally ~5µs, but an extended CP of 16.7µs is available for use in very large rural cells with significant multipath, or for multi-cell broadcast modes. For the most commonly-deployed bandwidths of 5, 10 and 20 MHz, there will be 512, 1024 or 2048 carriers.

The LTE downlink has a frame length of 10ms, divided into 1ms sub-frames and 0.5ms 'slots'. For the normal CP, there are therefore 7 OFDM symbols per slot. The most important granularity of the LTE physical later is probably the 'Resource Block' (RB), which consists of 12 carriers (180 kHz bandwidth) for the duration of one slot.

[34] https://www.ofcom.org.uk/__data/assets/pdf_file/0019/108127/in-car-mobile-signal-attenuation-report.pdf
[35] https://www.bbc.co.uk/sounds/help/questions/about-bbc-sounds-and-our-policies/codecs-bitrates

As is usual for OFDM systems, pilot or reference symbols are inserted to allow coherent demodulation. For a single antenna, four of the 84 symbols in a resource block will be reference symbols. Separate symbols are inserted for each antenna allowing the matrix of complex channel coefficients to be derived. The reference symbols also code for cell and sector identity.

Figure B.5: LTE Resource Blocks (1 RB = 12 subcarriers x 7 symbols)



A UE acquires a cell by means of primary and secondary synchronisation sequences (PSS, SSS) broadcast twice per 10ms frame. As well as synchronisation, these signals code for high level call parameters such as bandwidth, CP length and mode.

The main transport channel is the 'Physical Downlink Shared Channel' (PDSCH) which is turbo coded and can use a variety of modulation orders (QPSK or 16-, 64- or 256-QAM).

A 'Physical Multicast Channel' (PMCH) is also available for use in broadcast applications, where adjacent cells can form a single frequency network (SFN). Such applications are referred to as eMBMS (enhanced Multimedia Broadcast Multicast Services) or 'LTE Broadcast'. eMBMS was only standardised in LTE Release 9, and has not been widely implemented in practice, although many operators and broadcasters (including the BBC) have conducted trials.

Determining a definite limit of service is more complicated for 4G than for DAB or FM, owing the fact that the modulation and coding scheme (MCS) used by the PHSCH at any time is subject to negotiation between the UE and the network.

For many wireless systems a parameter referred to as Received Signal Strength Indicator (RSSI) is made available by receivers. This is generally an estimate of the total power falling in the receiver bandwidth, and will include not only the wanted carrier, but also receiver and external noise and interference from transmitters in the same network or from other systems.

In LTE receivers another parameter is also measured, which estimates only the wanted power received from a base station. This Reference Signal Received Power (RSRP) records the average power only in the scattered symbols that carry the cell-specific reference signals. As one such symbol carried only 1/12th of the power potentially available from all carriers in a Resource Block, and as there are N = 25, 50 or 100 Resource Blocks in a 5, 10 or 20 MHz channel, it is necessary to scale the RSRP to estimate the total wanted signal power.

$$\text{Total wanted power} = RSRP + 10 \log(12\,N)\ \text{dBm}$$

For a 10 MHz LTE signal, then, the scaling is 27.8dB.

If this total wanted power is now compared with the reported RSSI, the difference will correspond to the received man-made noise and inter- and intra-system interference. This value, the Reference Signal Received Quality (RSRQ), is reported to the eNB together with the RSRP to inform handover management.

B.3.2 Ofcom coverage obligation verification

The 800 MHz / 2.6 GHz auction includes a coverage obligation for the licensee of 811-821 // 852-862 MHz. This is expressed as:

"*The Licensee shall by no later than 31 December 2017 provide … [a] network that is capable of providing, with 90% confidence, a … service with a sustained downlink speed of not less than 2 Mbps when that network is lightly loaded, to users …in an area within which at least 98% of the population of the United Kingdom lives*".

The approach that Ofcom will use to assess compliance with this requirement is set out in the statement "*4G Coverage Obligation Notice of Compliance Verification Methodology*" (November 2017)[36].

The method requires that the signal to interference plus noise ratio (SINR) of the PDSCH needs to be above a threshold required to sustain a downlink speed of not less than 2 Mbps. The SINR values are based on a 3GPP Technical Report on 'Radio Frequency (RF) system scenarios' and derived on the basis of the Shannon bound with an appropriate offset for practical implementation (a factor of 0.6 in the downlink case).

For system bandwidths of 5, 10 and 20 MHz, the required SINR values are -0.3, -4.1 and -5.0 (the latter value being truncated to represent practical limitations).

Operator data for each network is then used to determine, in each UK pixel, the field strength of the best server, and the interference from the 20 other nearest sites. The wanted cell is assumed to be operating at full power and the others at 22% of maximum. A realistic propagation model (ITU-R P.1812) and antenna patterns are used in the calculations. Monte-Carlo methods are used to derive the statistical distribution of SINR in each pixel (assuming the location variability given in P.1812 and a 0.5 cross-correlation). A cell is deemed served if the SINR distribution exceeds the threshold with 90% probability.

Such a simulation exercise is beyond the remit of the current project, but it is useful to examine the assumptions made.

Ofcom assume that the handset has a noise figure of 10dB at 800 MHz. At an ambient temperature of 20°C this would give a power of -122.2dBm in the 15kHz bandwidth of a reference signal.

For the required SINR of -4.1, this implies that, in an interference-free environment, a 2 Mbit/s throughput could be achieved for a signal power of -126.3 dBm. Ofcom also assume a body loss of 2.5dB, increasing the required signal to -123.8 dBm.

[36] https://www.ofcom.org.uk/__data/assets/pdf_file/0020/108209/4g-coverage-methodology.pdf

Finally, a location variability of 5dB is assumed at 800 MHz. To ensure a 90% availability, this implies that a median pixel signal strength of -119.1 dBm would be required for outdoor data coverage. In practice, external noise and inter-cell interference will mean that significantly higher fields are required.

The original Shannon-derived SINR requirement for 2 Mbit/s data can be revised for the case of a high-quality audio stream at 320 kbit/s. For a 10 MHz channel, the SINR reduces from -4.1dB to -12.6dB, an 8.5dB difference. This might imply that, in a hypothetically interference-free environment, an median RSRP of around -128 dBm would provide a satisfactory service.

These figures, while not realistic, provide a useful lower bound for 4G coverage requirements.

The following values of building entry loss are assumed in the Ofcom work. It may be noted that these values are significantly greater than the 10dB assumed in the 'Connected Nations' methodology.

Table B.1: Ofcom assumed values for building loss in coverage assessment methodology

Band (MHz)	Building entry loss (dB)
791 – 821 / 832 - 862	13.2
880 – 915 / 925 – 960	13.7
1710-1785 / 1805-1880	16.5
1900-1980 / 2110-2170	17
2500-2690	17.9

B.3.3 Ofcom 'Connected Nations'

There is no mention of specific coverage thresholds in the 2013 'Infrastructure Report', when 4G had only just been launched.

In the 2014 report, it is noted that coverage information is submitted by all four operators in the form of maps of the median power received (with a 0dBi antenna) in 100m pixels. For 4G, an outdoor coverage threshold of -113dBm is applied. This relates, implicitly, to data but no service level (bitrate and availability) is associated with the power threshold. Ofcom assume that a power 10dB greater (-103dBm) is required to provide an indoor or in-car service.

In the 2015 and 2016 'Connected Nations' Reports the 4G thresholds (now explicitly for data, but still with no service level) have decreased to -115dBm (outdoor) and -105dBm (indoor/in car). Annex 1, 'Methodology', states but does not derive these.

The '2017 Report' refers to Ofcom drive testing and gives a change in definition, including 4G voice for the first time. The thresholds are now explicitly linked to a 95% chance of completing a 90-second call or receiving a 2Mbit/s data rate. The actual thresholds are only given in a footnote; "*4G voice services outdoor (-105dBm) and 4G data services outdoor (-115dBm)*". Thus outdoor voice is the same as in-car data. Puzzlingly, the report states that Ofcom work has shown that "*4G telephone call and data coverage requires a higher signal level than* *previously estimated*", despite the fact that the -115dBm outdoor data limit has not changed. Reference, however, to the accompanying data download description ('*about-data-mobile-local-unitary-authority-2017.pdf*'), suggests that the actual limits used are now -105dBm for outdoor voice and data and -95dBm for in-car voice and data.

The PDF version of the 'Spring 2018 Update' still gives the same dual 4G thresholds ("*4G voice services outdoor (-105dBm) and 4G data services outdoor (-115dBm)*"), but the accompanying data description again gives the -95/-105dBm limits. In the 'October 2018 Update', the text is corrected to refer to the *new threshold* for 4G of -105dBm for both voice and data, but the data description now includes both the single (-105dBm) and dual (-105 dBm voice, -115 dBm data) limits! It also mentions (but does not give a figure for) a lower threshold for lower speed data of at least 200kbit/s (footnote 12).

The published 2018 and 2019 'Connected Nations' reports continue to cite the -115dBm data and -105dBm voice criteria, but this appears to be an editorial error, as the accompanying spreadsheet data makes clear that the levels actually used are as shown in the table below:

Table B.2: Thresholds assumed in Ofcom's 'Connected Nations' reports.

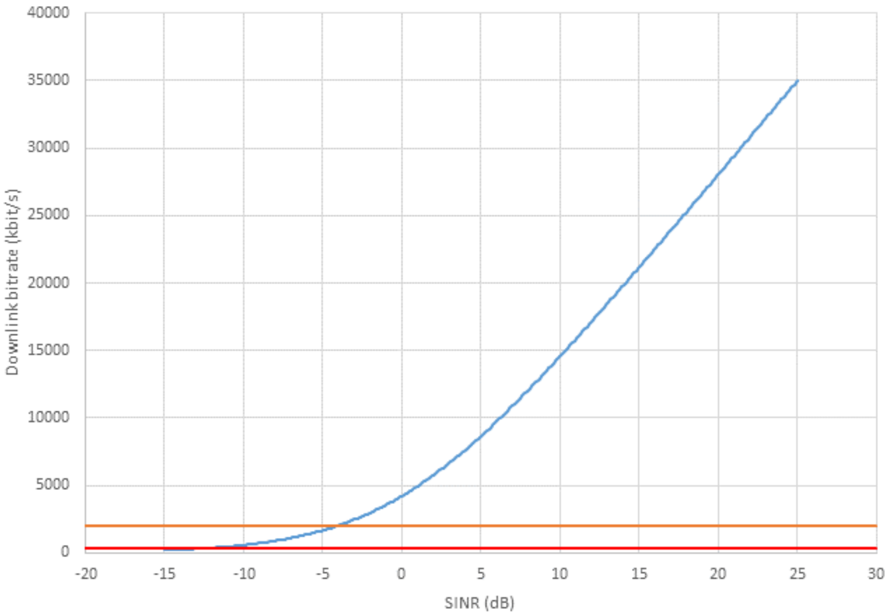
4G Service	Median power from 0dBm antenna in 100m x 100m pixel	
	Outdoor	Indoor, in-car
Voice	-105 dBm	-95 dBm
≥ 2 Mbit/s data	-105 dBm	-95 dBm
≥ 200 Kbit/s data	-115 dBm	-105 dBm

It is not clear what coverage availability is associated with these levels; the annual Reports refer to 95% while the 'Methodology' documents specify 98%.

B.4 Plum estimated threshold values

To provide an independent estimate of the coverage threshold for 4G streaming services, simple link budgets were developed.

These calculations are based on the assumption (see Annex A Section A.1 of 3GPP TR 36.942) of an offset Shannon fit to the actual LTE code-sets in use. The overall channel capacity curve for 10 MHz bandwidth is shown below, with horizontal likes identifying the 2 Mbit/s and 320 kbit/s rates. An implementation factor (α) of 0.6 is assumed.



The following assumptions have been made:

- We target a data rate of 320 kbit/s, which we understand is the highest rate served by BBC Sounds. Note, however, that this relatively high rate may not be available via cellular services.
- The modified Shannon curve predicts an SINR below -10dB for 320 kbit/s. The 3GPP TR truncates the curve at -10dB, so this is the SINR value adopted.
- Unlike the case for a portable radio, it is assumed that a smartphone user will expect to move freely within the house. A 20dB value is therefore chosen for building loss, to correspond to an 80% coverage target (from ITU-R P,2109 at 800 MHz),
- For the indoor and vehicle cases, a slightly (1dB) elevated receiver noise level is assumed due to man-made noise (see Annex D).
- For vehicle coverage, it is assumed that a degree of use co-operation can be expected in placing the phone is reasonably favourable position within the vehicle. The median value from Figure B.4 of 8.9dB is therefore adopted.
- No allowance is included for location variability. It is assumed that buffering is of sufficient length to require no offset from the median. This assumption may break down in the case of, e.g. stationary traffic (although it might be expected that road-traffic hotspots would be anti-correlated with coverage deficiencies). For the fixed indoor case, an entry-loss figure corresponding to 80% of indoor locations is assumed and it is also assumed that a degree of user-optimisation of location applies.

The table below presents the developed link budgets.

Table B.3: Indicative 4G streaming threshold values

Parameter	Outdoor	Indoor	Vehicle	
Frequency	800 MHz	800 MHz	800 MHz	Majority of 4G services tested were at 800 MHz
LTE Bandwidth	10 MHz	10 MHz	10 MHz	
Required bitrate	320 kbit/s	320 kbit/s	320 kbit/s	Allows for highest plausible stream rates
SINR	-10.0 dB	-10.0 dB	-10.0 dB	Bitrate implies -12.6dB. Truncated per 3GPP TR
Thermal noise	-103.9 dBm	-103.9 dBm	-103.9 dBm	kTB at 293K
UE noise figure	10dB	10dB	10dB	No measured data. Ofcom assumption.
Receiver noise	-93.9 dBm	-93.9 dBm	-93.9 dBm	
Assumed I/N	3	4	4	includes man-made noise (see Appendix D)
Total I+N	-89.1 dBm	-88.4 dBm	-88.4 dBm	
Required signal	-99.1 dBm	-98.4 dBm	-98.4 dBm	In overall bandwidth
RB in channel	50	50	50	25, 50 or 100 RB in 5, 10 or 20 MHz
RSRP at antenna port	-126.9 dBm	-126.2 dBm	-126.2 dBm	
UE antenna gain	-3dBi	-3dBi	-3dBi	Includes proximity effects. No measured data.
Required RSRP	-123.9 dBm	-123.2 dBm	-123.2 dBm	
Entry loss	0 dB	20 dB	8.9 dB	80% indoor, Ofcom vehicle median
Location margin	0 dB	0 dB	0 dB	Buffering assumed to allow for variability
Target outdoor RSRP	-123.9 dBm	-103.2 dBm	-114.3 dBm	
Ofcom 'low-rate' values	-115 dBm	-105 dBm	-105 dBm	

In the informal surveys reported in Appendix C, it was found that streaming audio was lost for an RSRP value around -119dBm to -120 dBm. This is in reasonable agreement with the 'required RSRP' value for the 'vehicle case'.

Taken together with the informal measurements, these predictions do not suggest that selecting the 'low-rate' threshold for the streaming case would be inappropriate. Further, formal, measurements would be needed to determine whether the ~5-9 dB of headroom that appears to be available is realistic. If this was the case, it might allow for the expected spread in handset performance, body loss variation and positioning within vehicles.

The closest alignment with the Ofcom 'low-rate' value is for the indoor case. This is misleading, however, as we have chosen a budget that would ensure a much greater location availability within the building.

Appendix C Informal surveys

It would be very valuable to undertake formal measurement exercises to make an accurate statistical determination of the coverage limits applicable for live audio steaming over a 4G or 5G channel. Such an exercise was not possible within the limited scope of the present study. It was felt important, however, to make some informal 'reality checks' on the limits suggested elsewhere in this report.

For this purpose a Sony 'XZ1 Compact' Android handset, with an O2 SIM, was used to listen to live radio streams with the BBC 'Sounds' app. A second app, 'Cellmapper'[37], was used to log GPS position and to record basic information about the LTE signal (RSRP, channel, eNodeB and sector ID). For all tests the handset was positioned on the dashboard of the car. The accuracy of the reported RSRP power levels is not known.

Comparisons were made with DAB reception, using a standard car radio with an external quarter-wave whip antenna.

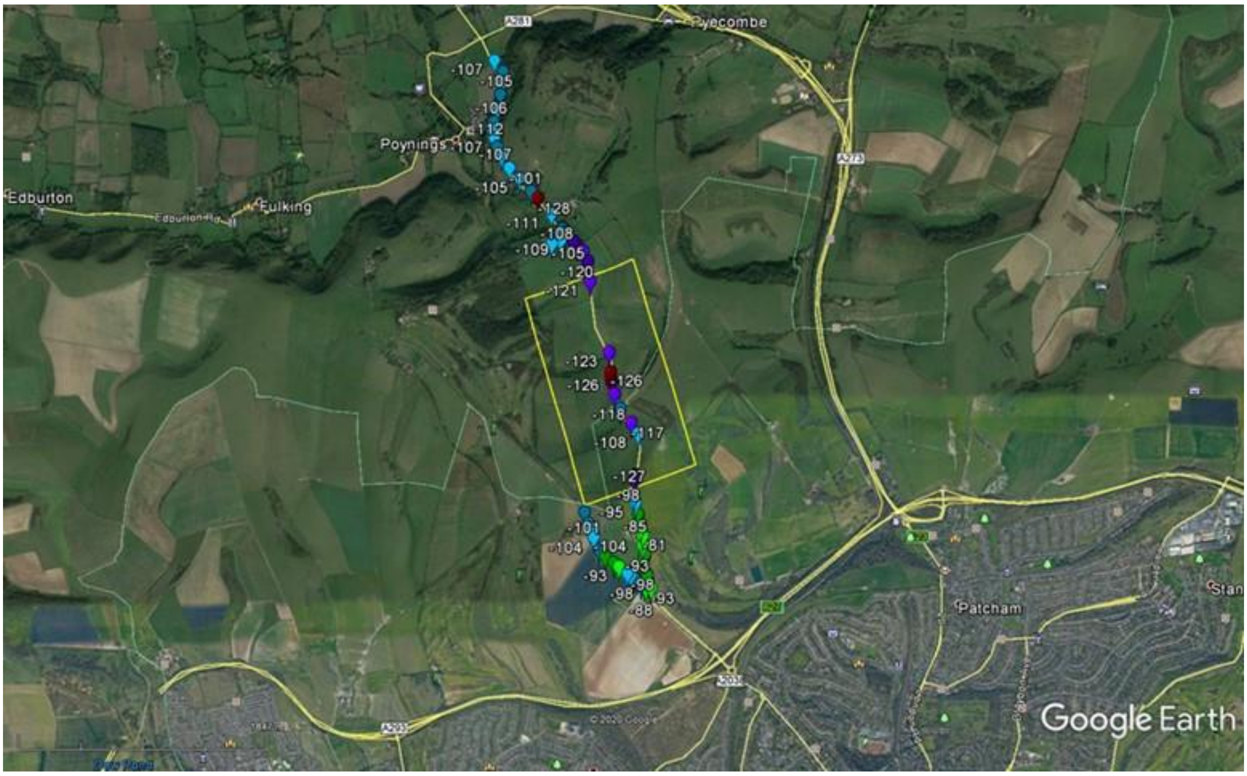
C.1 Brighton, Sussex

COVID-19 restrictions at the start of the study meant that opportunities for travel were limited; some time was spent looking for examples of poor cellular or DAB coverage in the South Downs around Brighton. It was found that areas that had coverage deficiencies a few years ago were now solidly served by both networks.

In an extensive search, no DAB deficiencies were found, and only one small part (1.7km) of a minor road in a valley suffered cellular drop-outs. The yellow box in the figure below indicates the section of the road where audio was lost from the Sounds app.

[37] https://www.cellmapper.net/map

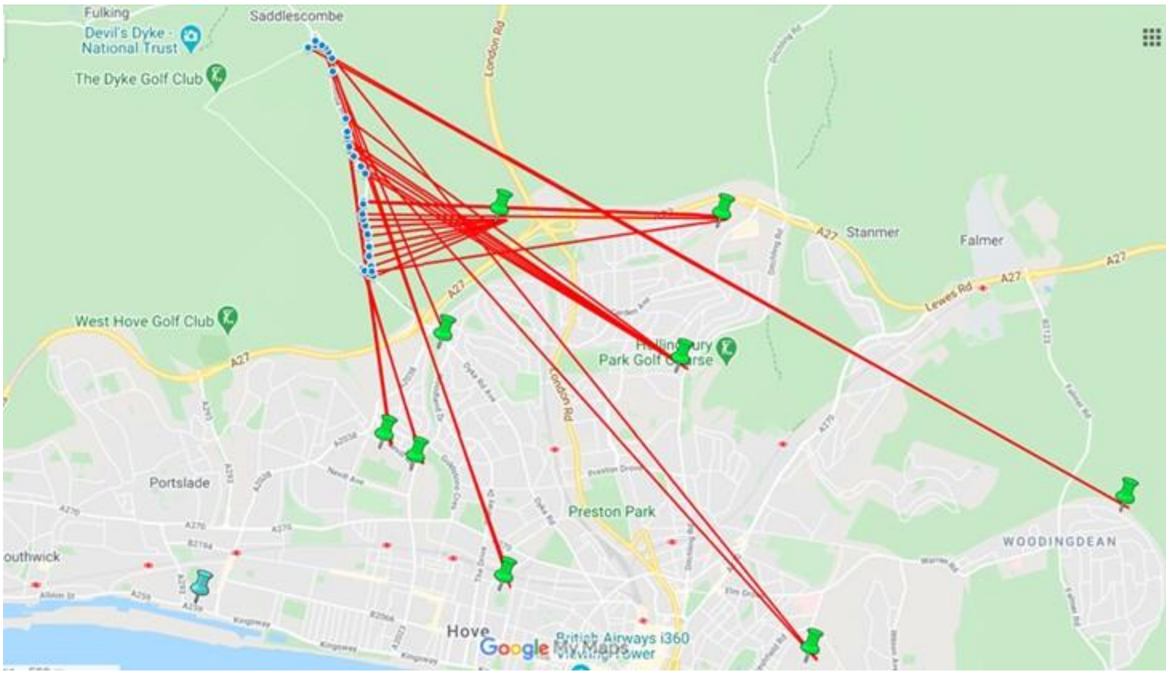
Figure C.1: Measurements in South Downs to north of Brighton



The audio was lost shortly after the RSRP level reported by the handset fell below -119dBm, and did not recover until the reported signal rose above that level for ten seconds or more.

An analysis of the 'Cellmapper' data showed that, as the handset entered and left the coverage deficiency, the connection switched rapidly between nine different eNodeBs, at ranges between 1.6km and 10km. This illustrates the complexity likely to be involved in making accurate predictions of not-spots without access to very detailed information about specific networks.

Figure C.2: Showing rapid change of eNodeB around coverage deficiency

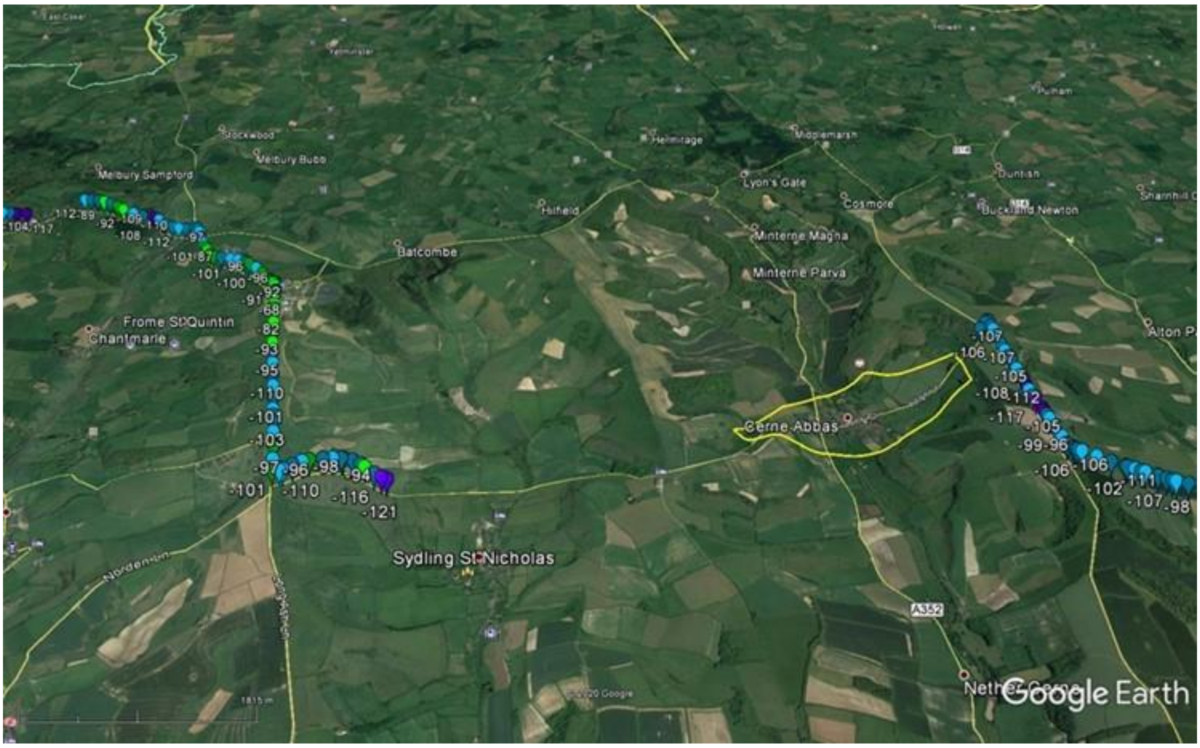


C.2 Cerne Abbas, Dorset

On a journey from Brighton (Sussex) to Beaminster (Dorset) on A-roads and motorways (~220km), neither DAB nor 4G/'Sounds' suffered from any drop-outs. The return was deliberately made along minor roads in West Dorset, and both DAB and 4G services were lost around Cerne Abbas.

Although the LTE service was lost as the RSRP level fell below -120dBm, the stream was sustained by a UMTS service (not indicated in the figure below) for a further 2km. The yellow box around Cerne Abbas indicates the approximate limit of both the cellular and DAB deficiencies.

Figure C.3: DAB and cellular coverage deficiency in Cerne Abbas area



The role of the UMTS network in sustaining the audio stream indicates the need for care, or appropriate measurement equipment, in any formal exercise to determine practical coverage thresholds for LTE or 5G/NR networks.

C.3 Prawle, Devon

A final set of measurements were made in the South Hams area of Devon. This is a potentially ideal location in which to investigate coverage thresholds, as the area is almost a peninsula with no eNodeBs to west, south or east. There is therefore less chance of the ambiguity due to overlapping service areas experienced elsewhere.

Figure C.4: Measured 4G coverage in South Hams, Devon

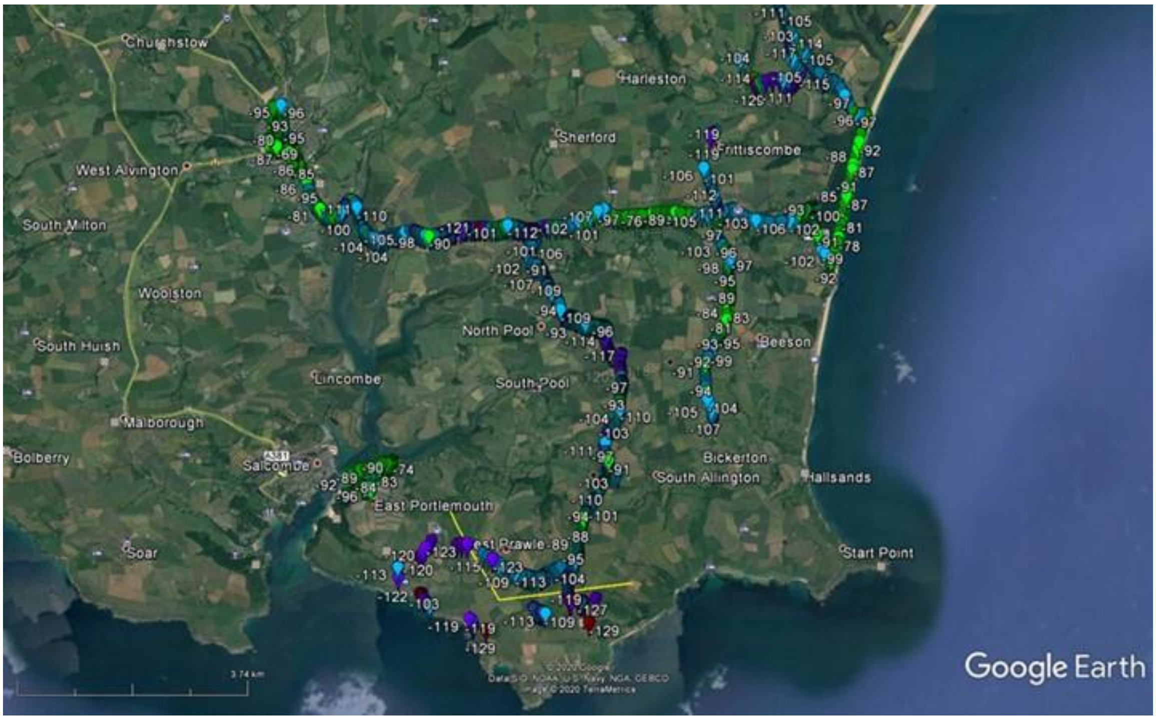


Figure C.5: Measured 4G coverage in South Hams, Devon (detail)

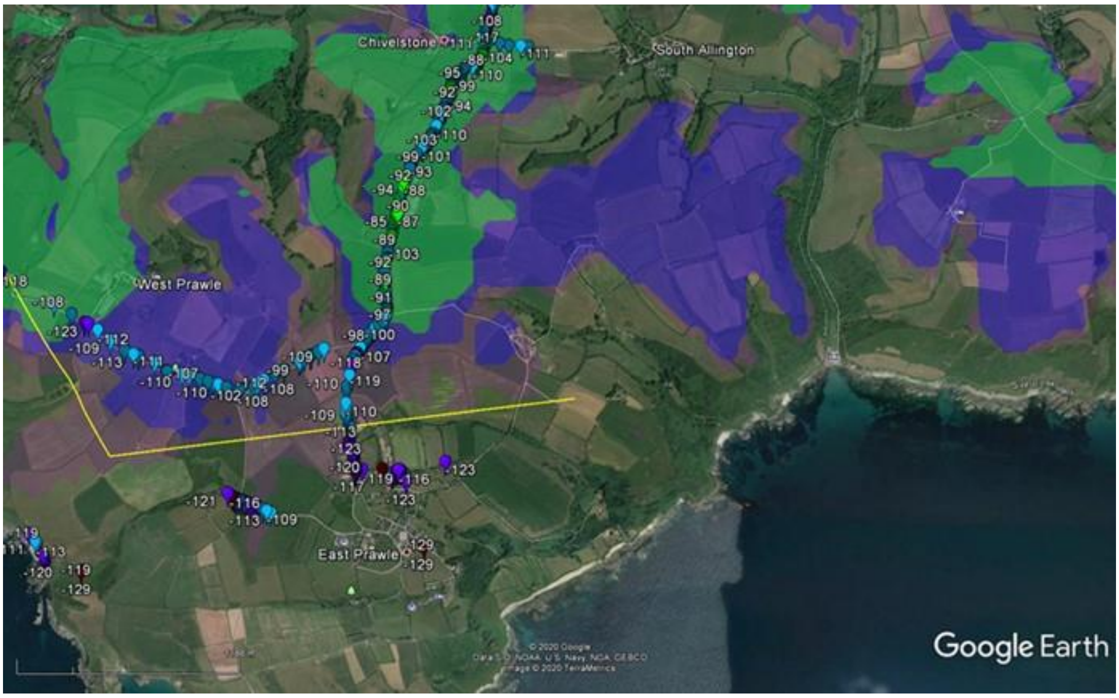
Even in this terrain of deep and winding valleys, with a relatively sparse network of base stations, it was found that 4G/streaming coverage was lost only on the outskirts of the village of East Prawle, as the terrain of the headland slopes towards the cliffs and away from local eNodeB sites.

The audio stream was lost to the south and west of the yellow line on the maps above, corresponding to RSRP levels between -115dBm and -120dBm.

A coverage prediction[38] was made, based on simple assumptions (that the five local eNodeB sites radiate omnidirectionally with an eirp of 61dBm at a frequency of 806 MHz).

The results below are contoured at -105dBm (brown), -100dbm (blue) and -95dBm (green). Allowing 10dB attenuation to the handset within the car, the results seem broadly consistent with the measurements. For simple, edge-of-network cases, such as those associated with TNS or EAS sites it may therefore be possible to make useful coverage predictions without a large dataset of detailed network parameters.

Figure C.6: Predicted 4G coverage, East Prawle.



DAB coverage was lost at no point in the area indicated.

C.4 Conclusion

It is important to state that these results can only be anecdotal. Not only are they very limited in scope, but the measurements of RSRP were made with an uncalibrated consumer device. It is also not known whether the RF performance of the Sony handset is good, average or poor with respect to the generality of handsets.

These caveats notwithstanding, the measurements would give some support to the view that the 'low-rate' RSRP limit of -115dBm may not be an inappropriate threshold value for audio streaming.

[38] Made using 50m terrain data and a version of ITU-R P.1812-4 tuned for rural use.

Appendix D Man-made noise measurements

To give a quick, but quantitative, assessment of the impact of indoor noise on DAB and cellular services, a limited set of measurements in one domestic property were made.

Folded dipole antennas were constructed and calibrated for frequencies within the DAB band, and between the 700 MHz and 800 MHz cellular allocations. The use of baluns ensured predictable performance and immunity from induced common-mode noise. The return loss at the frequencies used was in excess of 15dB.

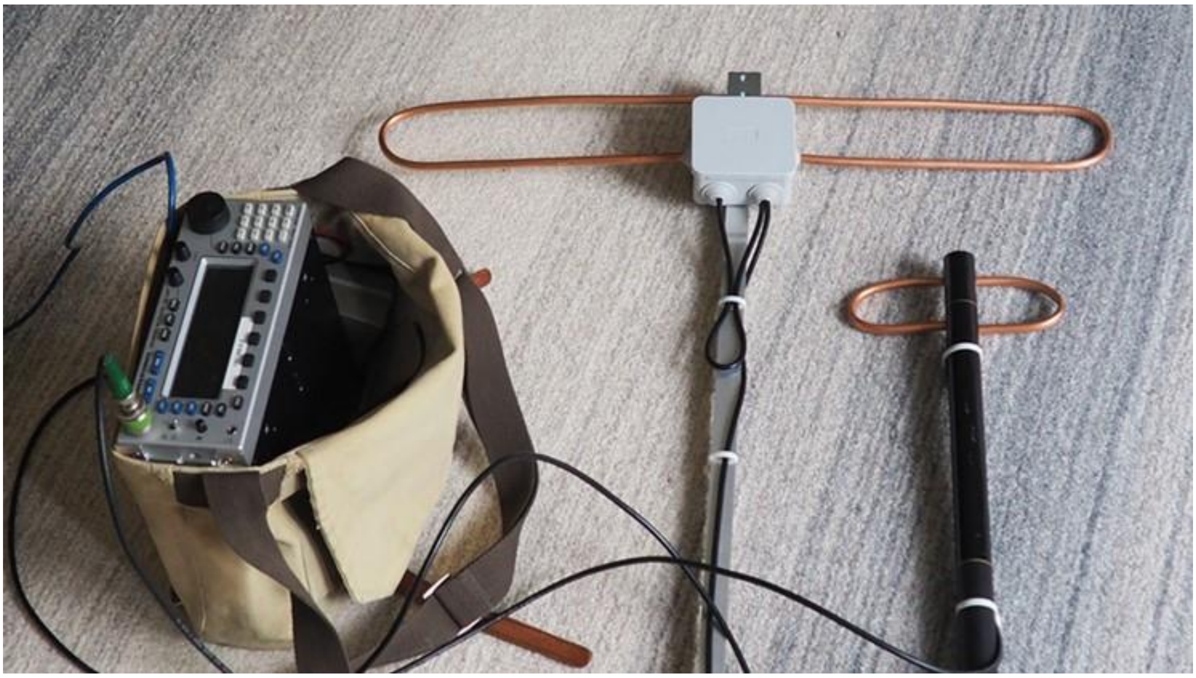
A Rohde & Schwarz EB200 measuring receiver was interfaced to a laptop computer, and configured to log continuous samples at two pairs of frequencies, one chosen to be unoccupied and the other at the centre frequency of a local transmission. The latter measurement was used to give an indication of practical signal-to-noise levels and of building entry loss.

Table D.1: Measurement parameters

Band	Clear frequency	Occupied frequency	Bandwidth	Detector	Polarisation	Measured NF
DAB	209.0 MHz	211.648 MHz (Whitehawk Hill)	120 kHz	Average	Vertical	9.8 dB
Cellular	788.5 MHz	793.5 MHz (5 MHz LTE)	120 kHz	Average	Vertical	9.8 dB

The EB200 has a noise figure given as *'<14dB, typically 12dB'*[39]. Samples were recorded with the receiver terminated by 50 ohms to derive the noise figures given in the table above (identical at the two frequencies).

Figure D.1: Measurement antennas and receiver

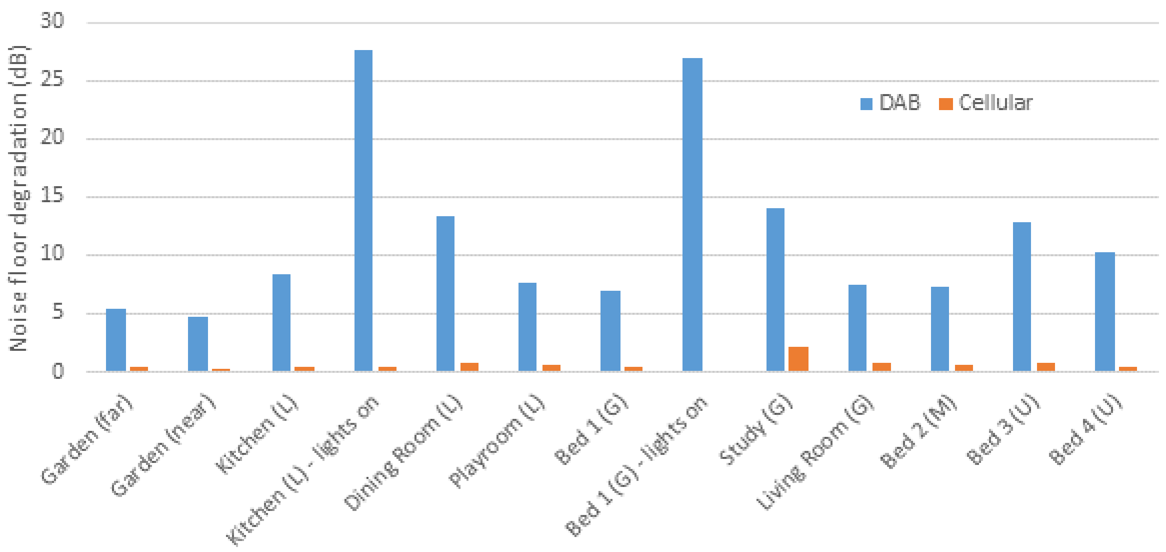


[39] <15.5dB above 650 MHz

Measurements were made by walking, quasi-randomly, in each room of the house in turn, aiming to cover the entire floor area as uniformly as possible. The Victorian house is of traditional brick construction, with a lower ground (L) floor opening onto the garden, a ground floor (G) at street level, a mezzanine (M) floor and an upper (U) floor.

It was already suspected that the LED ceiling lights fitted in the kitchen were a source of interference; measurements in the kitchen, and the bedroom above, were therefore made with these lights switch on and off.

Figure D.2: Measured indoor noise figures



The figure shows the dramatic impact of the kitchen lights, which degrade the DAB noise floor, in that room and the one above) by around 20dB. The DAB noise floor in other rooms was typically degraded by around 8dB, except for the study (14dB, several computers & monitors, router, etc) and the dining room (13dB, one computer and monitor).

It is evident that noise levels at 788 MHz are dramatically lower; The kitchen lights have no impact whatever at this frequency, and most rooms have a noise level only slightly above that found in the garden (<1dB above thermal in all cases). The only significant noise increase (2.2dB above thermal) was found in the study.

The increase in noise floor seen at 209 MHz in the garden can be compared with the model[40] of ITU-R Recommendation P.372. This gives a median '*external noise figure*' value of around 12.7 dB for a 'city' environment, which would imply a 5dB increase in noise power for a receiver with a noise figure of 9.8dB, almost exactly the result observed.

At UHF, the garden figure is close to the receiver noise floor (0.3dB); the ITU-R model does not extend to this frequency, but if extrapolated would also align with this observation.

It should be stressed that these measurements are necessarily anecdotal, concerning as they do a single house. A more rigorous exercise would also use a receiver with a lower noise floor and take into account the statistical distribution of the noise.

The implication, however, is that the relative vulnerability of indoor DAB receivers to interference from man-made noise should be explicitly considered in any comparison of indoor coverage.

[40] ITU-R P.372-14, equation 15