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Department for Transport

GB Rail Tunnel Signal Propagation & Wireless Connectivity Options

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Arup leads the Arup Alliance under the Department for Transport STARTwo framework in partnership with FCP and AECOM. Arup led the identification of technology options and assessment of deployment considerations.

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FCP led the overall assignment and analysis of Great Britian rail tunnels.

realwireless. independent wireless experts

Real Wireless is the leading independent wireless advisory firm, having expertise in all technical, regulatory, and economic aspects of wireless communications, supported by a comprehensive portfolio of in-house developed tools to analyse complex systems, enabling advice across all parts of the wireless ecosystem.

Using its tunnel solution experience, Real Wireless led the radio frequency propagation and user performance modelling for different tunnel types and scenarios, using a range of tools for prediction, calibration, and visualisation of results. Real Wireless was also instrumental in the technical solution and cost definition.

LS telcom Smart Spectrum Solutions

LS telcom is a global leader in spectrum efficiency delivering technologies and services to national and international regulatory bodies, to mobile and broadcast operators, to transport, critical infrastructure, defence, Public Protection and Disaster Relief and vertical markets. LS telcom optimizes spectrum management and spectrum use and enables new business models based on the internet of things (IoT).

LS telcom and ARTE Labs planned and carried out the radio frequency field testing to collect calibration data to validate the predictive modelling.

Executive Summary

This study is part of the Department for Transport's objective to understand the practical and technical barriers to improving mobile connectivity on the railway.

Research by Transport Focus highlights[i] that while mobile connectivity for some can be good, it remains poor for many rail passengers, irrespective of their means of connection: whether 'direct to passenger' through the window using their existing mobile subscriptions, or 'indirectly' via the train wifi which today is also reliant on mobile network operator connectivity.

Although tunnels only cover approximately 2 percent (330km) of Great Britain's railways by length (those with tunnel bores over 50 metres long) they, by their nature, present a particular challenge for signal propagation. This is often exacerbated by deep cuttings associated with the lead up to their entrances, making voice call and internet connection drops almost inevitable. All things considered, addressing tunnel propagation would contribute to general improvements to passengers' mobile connectivity experience.

Today few rail tunnels in Great Britain are fitted, with exceptions such as the Severn Tunnel linking Wales and England. Retro-fitting a tunnel, especially many of our Victorian era ones, can also be incredibly challenging given space constraints, environmental conditions such as ground-water ingress, and of course the potential need to close the tunnel for works with possible disruption to passenger and freight services.

The study offers a technical examination of tunnel propagation loss from both a theoretical and practical viewpoint. This highlights the difficulties associated with predicting tunnel signal propagation given the wide range of contributory factors, not just the obvious ones of how a tunnel is constructed and its width and length. Practical radio frequency testing, with support from key partners, at Dudley, Standedge and Copenhagen tunnels has been used to validate findings.

Analysis has also been undertaken of solutions capable of delivering improved mobile connectivity. These include current 'direct to passenger' 4G/5G mobile technologies, using licensed spectrum between 700 and 3,800MHz, and alternative 'indirect' train-to-track wifi at 5.5GHz and emerging high-capacity line-of-sight technologies using millimetric wave at 26 and 60GHz. In the latter solutions the external signals are redistributed to passengers using existing on-train wifi services or potentially in the future cellular small cells.

From this work it has been possible to identify six typical tunnel types found on GB railways reflecting the past, present and future of construction materials ranging from brick lined, unlined rock and reinforced concrete, and hence what solutions would be most suitable. Such solutions include 'Near Portal', 'At Portal' and 'In Tunnel' designs.

The other key contributory factor is cost. For each solution, indicative whole-of-life costs have been developed, to help understand the fixed and variable costs.

Drawing these strands together an options selection flowchart is intended to support decision making, guiding the selection of appropriate tunnel solutions depending on tunnel type, technology and spectrum considerations and the desired user experience requirements.

The overall objective is to provide relevant guidance to the rail and telecommunication industries.

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Disclaimer

This report has been prepared by the Arup Alliance for the Department for Transport and may be published by them. In carrying out our work and preparing our report, we have worked in accordance with the terms of our contract of engagement. Our report may not therefore have considered issues as they relate to any third parties. Accordingly, we assume no responsibility or liability whatsoever to any third parties who are shown or gain access to our report in relation to the report's contents either by its publication or as a result of being shared by our client. Any use such third parties may choose to make of our report is entirely at their own risk. In addition, to the extent that the parties involved with the production of the report have relied on information and data provided by our client, and other literature referenced in order to produce this report, we make no representation as to the accuracy or currency of any such information or data.

1 Introduction

This study is part of the Department for Transport's (DfT) objective to understand the practical and technical barriers to improving connectivity on the railway.

1.1 Background

The National Infrastructure Commission (NIC) report of 2016 [1], and reiterated in 2020 [2], set out a recommendation that:

> *"[Recommendation 3] Rail passengers should have high-capacity wireless connectivity. This could be achieved through a delivery model that utilises trackside infrastructure to provide an open and accessible mobile telecommunication and backhaul network that is fit for the future respectively."*

The 2020 NIC report cited projects underway to improve mobile connectivity through train-borne wifi routers operating over conventional 4G channels from mobile network operators using licensed spectrum as well as innovative proprietary 5G solutions using unlicensed spectrum at millimetric wave frequencies (60 GHz) being pioneered by Blu Wireless and FirstGroup's South Western Railway [3].

However, Transport Focus research has continued to report that passengers still have reason to prefer direct access to their Mobile Network Operator (MNO) for 96 percent of data calls compared to train-borne wifi [4, 5], this is likely to be linked to uneven coverage along the line of route.

Direct access between passenger devices and their MNO need not mean a direct physical data link. This is important because a recent DfT study on rail carriage attenuation [6] found that passenger devices within rail carriages face a far wider range of signal attenuation, from 5 dB to100 dB, compared with the 7 to 10 dB typically allowed for domestic dwellings or motor cars. Signal attenuation on trains varies by rail carriage design, passenger location within the passenger saloon, how passengers use and hold their devices, and the presence of other passengers and their belongings.

The rail carriage report proposed that much of this additional train loss could be avoided using an external train antenna and indirect 'technology agnostic' on-train gateways serving all passenger devices on the train. Such an approach is already common for the provision of on-train wifi services but not yet for handling the bundled traffic of multiple MNOs (for example through the provision of on-train multi-carrier small cells).

Passenger wireless connectivity becomes an even greater challenge within railway tunnels and deep cuttings, which cause more attenuation. Hence, the need to understand the wireless signal propagation characteristics of mainline rail tunnels in Great Britain (GB) and possible, economical, solutions that be fitted and integrated with existing MNO networks.

Few rail tunnels are currently fitted, and any tunnel solution must deal with signal propagation losses throughout the tunnel not just at the entrances (portals). Tunnels differ in length, cross-sectional profile, alignment, lining material, and humidity and groundwater conditions. They vary in age, operate at different line speeds and many have limited space or are already full of other tunnel infrastructure and services.

Signal improvements (or addressing the complete lack of a signal) may be provided by directional antennas or distributed radiating cable, located near or at tunnel portals, or fitted throughout the length of longer tunnels. They must exploit allocated spectrum and signal bandwidth to provide sufficient signal throughout the tunnel to meet the wireless connectivity needs of passengers. The means of access is also an important consideration with due consideration given to direct connectivity approaches, whereby the signal is delivered direct to the passenger's mobile device, or indirect approaches where externally fitted antennas on the train roof or front of the train relays the signal to on-train gateways for re-distribution.

1.2 Purpose

The aim of this study is to research wireless signal propagation loss within GB railway mainline railway tunnels and deep cuttings, to propose potential tunnel fitment solutions based on standard 'blueprint' architecture propagation and provide guidance to business sponsors wishing to compare the alternatives.

1.3 Audience

This report is expected to be of interest to the DfT, the Department for Digital Culture Media and Sport (DCMS), Network Rail (NR), Future Railway Mobile Communications System (FRMCS), the National Infrastructure Commission (NIC), Ofcom, Transport Focus, Joint Operator Technical Specification for Rail (JOTS Rail) Group of Mobile Network Operators (MNO), Rolling Stock Operating Companies (ROSCOs), Rail Delivery Group (RDG), Train Operating Companies (TOCs), and the current and future supply chain.

1.4 Scope

The study covers a wide range of wireless connectivity technology and spectrum:

- Cellular mobile network operators using 4G/ 5G mobile technology in licensed spectrum allocations between 700 MHz and 3,800 MHz.
- Existing trackside track-to-train technologies using modified wifi at 5.5 GHz.
- New proprietary technologies offering high-capacity line-of-sight links within the millimetric wave spectrum bands at 26 GHz and 60 GHz.

The study examines qualitative signal propagation principles, taking note of previous research and international case studies relevant to the GB context, desktop RF modelling and analysis. RF test measurements of carrier wave signal propagation loss were also conducted at three non-operational tunnels including Dudley, Standedge (Old) and the Eastern bore of Copenhagen Tunnel near King's Cross.

1.5 Acknowledgements

This report was developed in partnership with Arup, FCP, Real Wireless, and LS Telcom. The project team consulted with several stakeholders to gather information on railway assets, products, performance, signal level measurements, best practices, and to validate our assumptions.

The JOTS Rail team and Network Rail Telecom representatives provided valuable insights and inputs on tunnel coverage solutions. Manufacturers who were consulted and provided valuable technology insights include CommScope, SOLiD, Samsung, EvoRail, Icomera, Radwin, Radio Design and Eupen. Siroda, HS1 and Network Rail were also very helpful in sharing measurement data that was used for the calibration (and validation) of the propagation and prediction models used in this project.

The RF test measurements relied on the permission and active co-operation and support from the owners, operators (and their contractors) of the following tunnels:

- **Dudley** Tunnel is operated and maintained by Black Country Innovative Manufacturing Organisation (BCIMO) who provided free access.
- **Standedge (Old)** Tunnel is owned, operated and maintained by NR. The tests were supervised by the NR Route Telecoms Minor Works Eastern Region Team.
- **Copenhagen** (Eastern bore) tunnel is owned, operated and maintained by NR. Essential support during the test session was provided by ADComms Ltd.

2 How to Use this Guide

This report has been written partly as a technical engineering study of rail signal propagation within rail tunnels and partly as a guide to a business sponsor seeking a high-level understanding of the wireless infrastructure options to address specific rail tunnels and associated tunnel approaches on GB railways.

The proposed solutions and recommendations are based on the results of measurements, modelling and insights of signal propagation within railway tunnels by the study team, backed by other sources of information obtained from suppliers, other stakeholders, and literature review.

This study has confirmed how difficult it is to predict the range of signal propagation within any specific railway tunnel. Although this report offers a systematic high-level options selection process populated with data to make specific recommendations, it also discusses the assumptions made and the many factors that influence wireless connectivity in railway tunnels. Whilst the study should provide useful insight, any business sponsor is advised to conduct their own surveys to validate any preferred option.

2.1 Audience for the report

This report has been written primarily for two audiences:

- **Engineering** detailing the theoretical and practical aspects of the technical rail tunnel signal propagation study, designed to help the GB rail industry to predict the signal propagation characteristics of its tunnels at carrier frequencies already in use, from 700 MHz to 3,600 MHz by licensed cellular MNOs, 5,500 MHz for unlicensed wifi and millimetre wave spectrum becoming available at 26 GHz and 60 GHz. Any signal propagation predictive modelling has been backed by RF field testing and a qualitative assessment of signal propagation principles. This work is covered mainly in Sections 3 to 9 and the supporting appendices.

- **Business sponsors** detailing the high-level considerations and options associated with fitting out specific railway tunnels to support a specific mobile connectivity requirement. The option selection process is introduced in Section 2.2 and developed in Sections 7 through 9 where it is also illustrated with worked examples. Sections 3 to 6 and the appendices provide further background material on principles and assumptions.

2.2 Structure of report

The report is structured as follows and as illustrated in Figure 1:

- **Section 3** provides an overview of GB rail tunnels and explains how a reduced set of six tunnel types has been selected for typical signal propagation analysis, coverage range forecast, and tunnel fitment solution modelling.

- **Section 4** explains direct versus indirect connectivity, the demand for passenger wireless connectivity, and how it may be fulfilled by wireless technologies.

- **Section 5**, supported by Appendix 3, discusses RF signal propagation principles that help to explain the typical signal propagation loss (dB) versus range (m) characteristics measured in real railway tunnels.

- **Section 6** looks beyond the fitment of a single tunnel to anticipate the needs of full line-of-route deployment and practical railway operation. It reflects on the minimum length of tunnel to justify signal strengthening, additional train losses caused by the train, the need for additional onboard equipment for indirect connectivity, and arrangements to ensure seamless cell handover.

- **Section 7** introduces the ‘blueprint’ architecture elements used to construct tunnel fitment solutions in Section 8 and how the usable signal propagation range is determined for each and compiled into range lookup tables used in Section 9. Options that lack range may be ruled out immediately.

- **Section 8** explains how the ‘blueprint’ architecture elements combine into potential tunnel fitment solutions and practical deployment considerations.

- **Section 9** discusses the wider commercial context affecting tunnel fitment, introduces a simple relative cost model and how it may be used to compare different tunnel fitment options with the aid of worked examples.

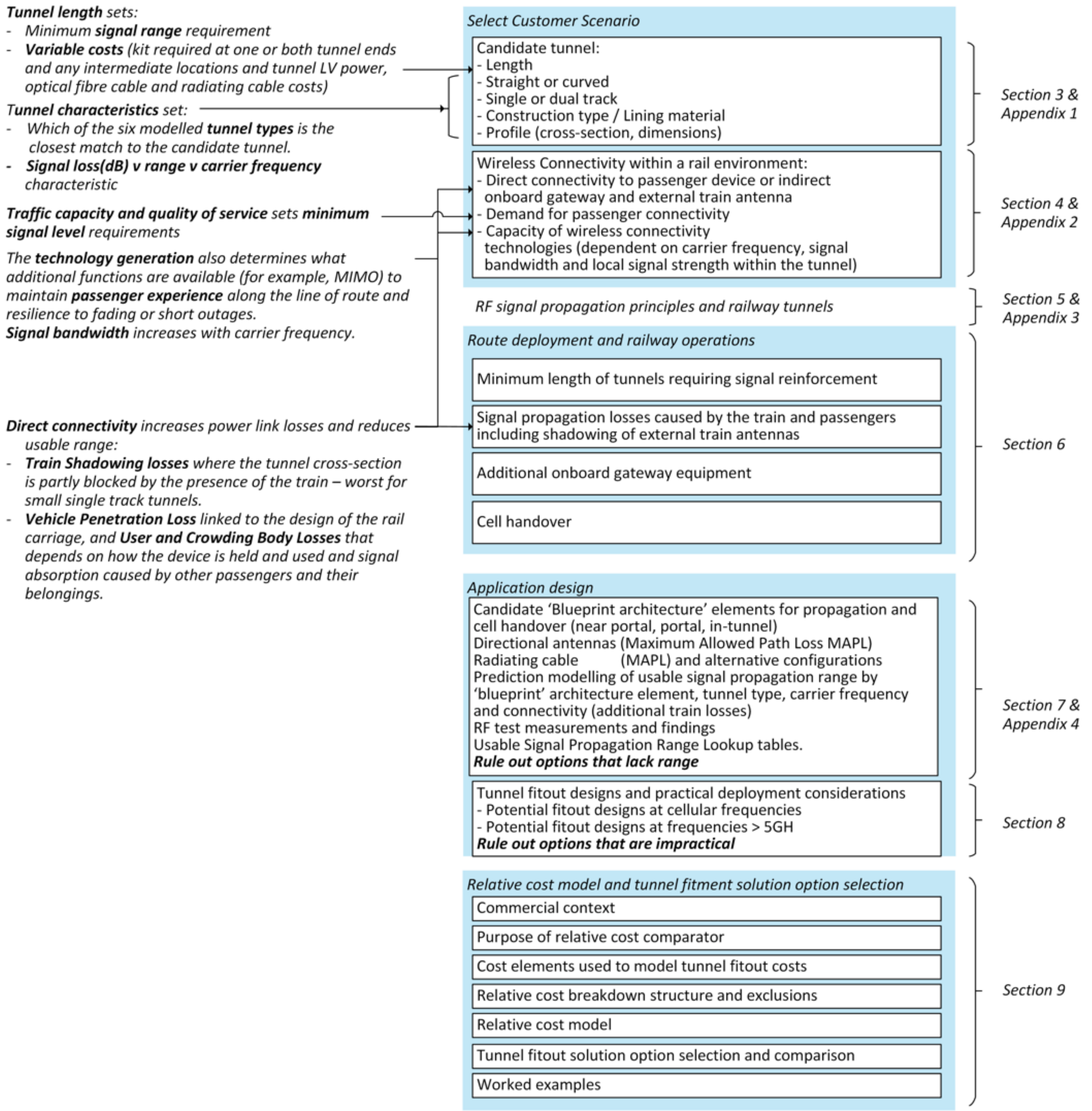


Figure 1 - Report structure including option selection process

Concluding the document:

- **Section 10** presents conclusions.
- **Section 11** suggests future opportunities to improve the prediction of railway loss in railway tunnels.
- The glossary explains acronyms and abbreviations used in the text.

The appendices provide supporting information:

- **Appendix 1** sets out sources and assumptions made during the analysis of GB mainline railway tunnels in Section 3.
- **Appendix 2** presents detailed technology configurations and assumptions discussed in Section 4 that have a bearing on the Maximum Allowed Path Loss (MAPL) discussed in Section 7.
- **Appendix 3** presents supplementary information on signal propagation principles to support Section 5.
- **Appendix 4** presents the results of RF signal propagation loss measurements carried out at Dudley, Standedge (Old) and Copenhagen (Eastern bore) tunnels.

3 Tunnels within the rail network of Great Britain

This section describes the GB railway tunnel assets and analyses the characteristics that affect signal propagation including number of tracks, their cross-sectional profile, size, length and alignment, and their construction material and inner lining.

This information has been used to characterise the typical tunnel types found on the GB mainline railway. A combination of six distinct tunnel types and tunnel lengths has been used to develop the representative wireless connectivity options set out in Sections 7 to 9.

3.1 Evolution of GB rail tunnel design and construction

Tunnels have always been an important part of railway design and construction. Rail-based wagons were used from the end of the eighteenth century to move ore from mine workings and these needed direct routes through difficult terrain, including tunnels to maintain the steady variations of gradient and curvature needed by the rolling stock available. This continued with the introduction of steam locomotion and rapid expansion of mainline railways from the 1840s onwards.

Design and construction techniques evolved to balance operational need, technical difficulty, and economics. The tunnels needed to support the basic gauge and ventilation requirements of the rolling stock, the construction techniques had to adapt to: available access to the alignment, ground, water and geological conditions, construction materials and available skilled labour and plant, speed of construction, and cost.

Tunnels through solid rock are self-supporting but difficult to drill and blast through. Tunnels near the surface can be ‘cut and cover’, dug out as a trench and then constructed with a lining comprising sidewalls and roof strong enough to bear the weight and hydrostatic pressure of the ground above once covered. Deeper tunnels had to be driven through the ground, progressively lined to prevent collapse or flooding, and ventilated for the tunnellers.

Table 1 describes seven construction types of operational GB mainline railway tunnels:

A. Brick arches with iron beams
B. Brick or stone arches
C. Concrete
D. Beams on abutments (side walls)
E. Unlined rock
F. Cast Iron Segmental or
G. Mixed

Type	Description
 Cheam Station Source: G Beecroft 2009	**Type A: Brick arches with iron beams (popular during 19th Century)** Jack arches comprise shallow brick arches that span between the flanges of iron or steel beams to form a roof structure for cut and cover tunnels. They are usually supported on brick abutments (side walls).

Type	Description
 Dudley Tunnel Source: Study team	**Type B: Brick or stone arches (most common design 1850 to 1900)** Brick (or less commonly stone) arch tunnels form most railway tunnels in GB. Depending on the depth, brick arch tunnels were either built by 'cut and cover' or bored. Arch materials need only compressive strength as they are pressed down from the ground above. The thickness of the brick lining is generally between 4 and 8 rings of brick, depending on the depth and local ground conditions. Brick tunnels could be used down to a depth of 100 metres, with stone usually needed for deeper tunnels.
 Thameslink Canal Tunnel Source: Network Rail  Grimstone Tunnel, Dorset Source: Network Rail	**Type C: Concrete (late 1940s onwards)** Pre-cast concrete linings were not common until the late 1940s and were developed in response to the shortage of grey iron. They are now the preferred form of construction for new tunnels and have been used on HS1, Thameslink, Crossrail, and now HS2. Circular **pre-cast concrete linings** are used for bored tunnels and are placed using erectors within Tunnel Boring Machines. Pre-cast linings can also take the form of box sections or arches, capable of supporting large surcharges up to 30m. They allow rapid and cost-effective construction on-site. Cut and cover tunnels can also be constructed using a **rigid in-situ concrete box** structure. Open cut construction is cheapest where space permits. However, in urban areas where space is tight, the side walls are constructed first (using piling or diaphragm walling techniques) to support the ground outside the tunnel while the space between is excavated. The base and roof of the structure is then constructed, before being covered over. **Sprayed or in-situ concrete** has four primary applications: • To line non-self-supporting rock tunnels by penetrating joints and fissures to strengthen loose rock, prevent deformation and protects the rock against weathering or other degradation. • As a secondary lining to provide a smooth finish or additional protection. • As a primary lining in special situations where there is no simpler alternative, such as around openings and at junctions. • To repair and stabilise existing brick tunnels either over localised areas or larger scale relining.
 Source: Network Rail	**Type D: Beams on abutments (now superseded by Type C concrete)** A 'cut and cover' tunnel with discrete simply supported iron or steel beams spanning abutments (side walls). The beams are usually spaced and roofed over with steel deck plates or concrete deck units able to support the load above. Abutments are generally brick but can be stone or concrete.

Type	Description
 Moncrieff Tunnel Source: Network Rail/ Fairhurst	**Type E: Unlined rock** Rock tunnels would have traditionally been excavated using handheld power tools, mining machines or, for harder rock, by 'drilling and blasting', where blast holes are drilled and loaded with explosive, and the blasted rock removed. Tunnels in virtually intact hard rock, with a rock-block size (the spaces between joints) equal or greater than the size of the tunnel bore, will be self-supporting and may not require a supporting lining. This is due to the 'ground-arch' effect, whereby the ground load is transferred around the sides of the bore. If the ground arch is permanent, the stand-up time is infinite, and no support is required to prevent collapse. However, some rock types will be subject to gradual degradation or weathering leading to fissures, spalling, and local areas of failure. Remedial work such as installation of rock netting, rock reinforcement dowels or a secondary lining would be needed to reduce the risk of falling rock and debris.
 Source: Transport for London	**Type F: Cast Iron/ Spheroidal Graphite Iron (SGI) Segmental (1890 to mid-20th Century)** Cast iron segmental tunnel linings were first used in deep running tunnels on the City and South London Railway in 1886 and were used extensively for the deep London Underground Tunnels. They were superseded as confidence was gained in Type C concrete when iron was scarce and increased in price. Cast iron tunnels are generally bolted and constructed using a shield. In non-cohesive ground the lining is erected in the 'tail skin' of the shield, which overlaps the previous erected ring and the void behind the lining is filled with grout to form a watertight seal. Iron tunnel linings are traditionally manufactured from grey iron but have been replaced with Spheroidal Graphite Iron (SGI) which has a higher tensile strength, meaning thinner and larger sections can be used, making them more economical. Nowadays SGI linings are most used for sections with special loading conditions, such as stations, junctions and around openings.
 Rowley Regis Tunnel Source: Network Rail	**Type G: Mixed** For some tunnels the material and /or type of construction varies along their length, meaning they cannot be placed into any one of the above categories A through F. This might occur if the original tunnel was extended at a later stage or if a tunnel was built through varied ground conditions that required different tunnelling techniques or linings. Some tunnels, particularly older brick arches and unlined rock tunnels, may have had secondary linings (such as sprayed concrete or steel tunnel liner plates) installed where sections of the tunnel had failed or required strengthening.

Table 1 - GB railway tunnel design and construction techniques

3.2 Details of GB tunnels

Data provided by DfT and Network Rail show that there are 634 operational tunnels on the GB mainline, although 12 of these lack operational signalling (Appendix 1).

See also Table 36 in Appendix 1.1 for assumptions.

3.2.1 Design/ construction type

Some designs are much more common than others (Table 2).

Type	Description)	Number	As % of Known
A	Brick arches with iron beams	20	4 %
B	Brick or stone arches	357	69 %
C	Concrete	18	3 %
D	Beams on abutments (side walls)	6	1 %
E	Unlined rock	16	3 %
F	Cast Iron Segmental	6	1 %
G	Mixed	97	19 %
Total		***520****	***100 %****

* Excludes 114 tunnels from the total of 634 operational tunnels for which a summary of construction material was not readily available.

Table 2 - Tunnel population by construction type

Almost 70% of GB tunnels are of brick or stone arch construction, 3% unlined rock, and 19% used a mix of at least three different construction techniques.

Although concrete has been used in less than 4% of the tunnel population, it has become the favoured design and construction technique since the middle of the 20th Century. Pre-cast concrete segments and elements and sprayed concrete techniques have been used in the Channel Tunnel, HS1, Thameslink Canal tunnels, Crossrail, and now HS2.

3.2.2 Length

Half the tunnels are less than 260 metres long, 35% between 260 metres and 1,000 metres and 15% longer than 1,000 metres (Table 3).

Length Classification	Description	Number	As % of Total
Bridge [Ignored]	Length ≤ 10 m	1	< 1 %
Very Short	10 m < Length ≤ 50 m	36	6 %
Short	50 m < Length ≤ 260 m	268	44 %
Medium	260 m < Length ≤ 1,000 m	222	35 %
Long	1,000 m < Length ≤ 5,000 m	96	15 %
Very Long	Length > 5,000 m	1	< 1 %
Total		***634***	***100 %***

Table 3 - Tunnel population by length

3.2.3 Operational – tracks per tunnel bore

More than two thirds of the tunnels are single track (Table 4).

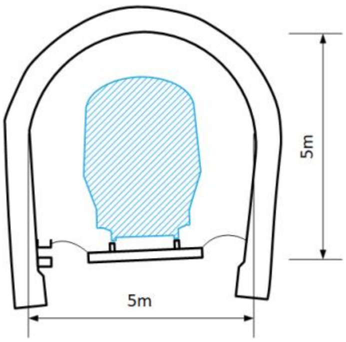
Description	Number of Tunnels	As % of Total
Single Track	145	69 %
Dual Track	437	23 %
Unknown	52	8 %
Totals	***634***	***100 %***

Table 4 - Tunnel tracks per bore

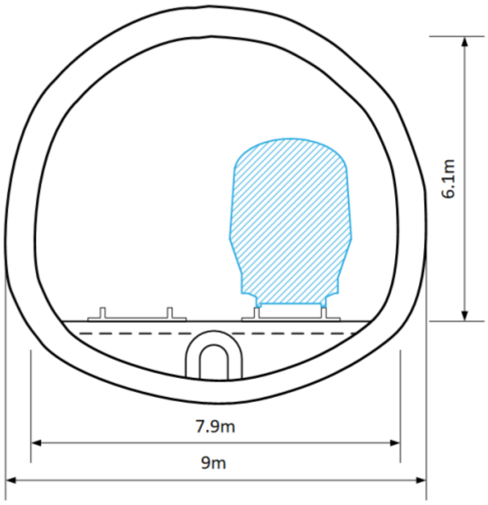
3.2.4 Tunnel cross-sectional profiles and dimensions

Typical construction profiles and dimensions for standard tunnel types are shown in Figure 2.

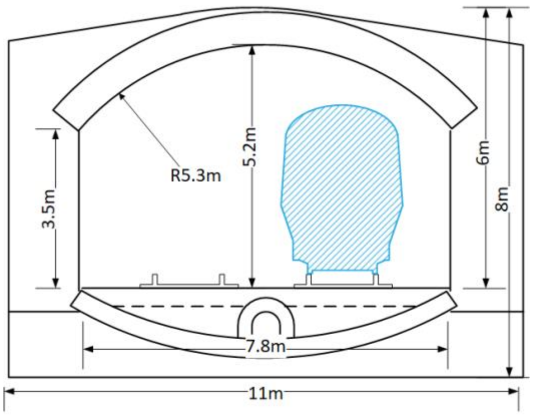
Most brick tunnels are sized to fit standard gauge track, whereas modern concrete tunnels vary in diameter according to line speed.



a) Bored brick arch, single-track



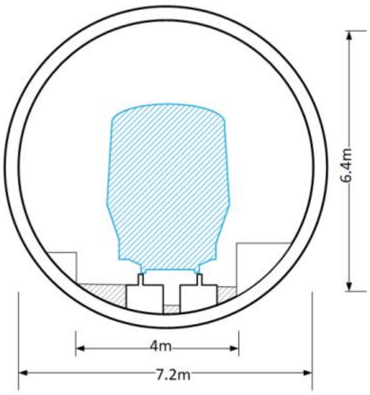
b) Bored brick arch, double track



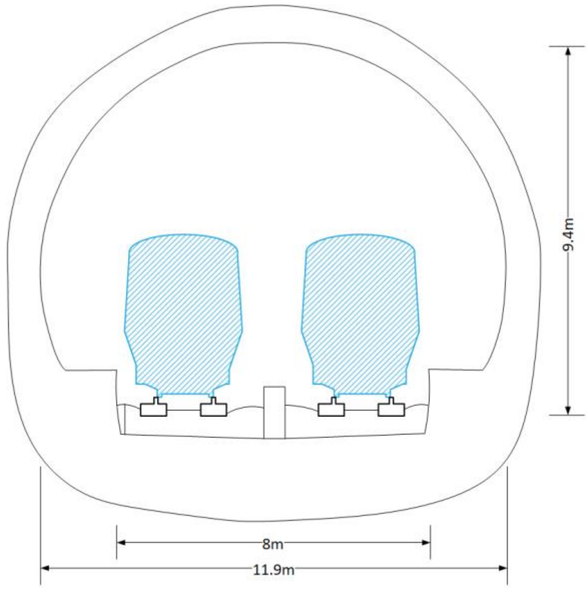
[c) Not used]

d) Cut and Cover brick arch, dual track

Figure 2a) through d) - Standard tunnel profiles



e) Concrete, single track (HS1, London)



f) Concrete, dual track (HS1 North Downs)

Figure 2e) through f) - Standard tunnel profiles

3.2.5 Curvature

The permanent way data (Appendix 1) records horizontal curvature as versine measurements every 50 metres along the track to show the deviation of the outer track at the midpoint of a 100 metre straight chord. These data come from measuring a sample comprising 275 km of track. Table 5 shows the distribution of these versines but also converted into radius of curvature and included angle (see also Appendix 1.2).

Curvature Classification	Versine (metres)	Radius (metres)	Included Angle (2Ω)	Data points	As % of Total
Straight	0 m ≥ V ≤ 0.1m	∞ ≥ R ≤12,000m	0° ≥ 2Ω ≤ 0.5°	3,948	72
Slight	0.1m < V ≤ 2m	12,000m> R ≥ 620m	0.5° < 2Ω ≤ 9°	1,205	22
Medium	2m < V ≤ 5m	620m > R ≥ 250m	9° < 2Ω ≤ 23°	269	5
Tight	V > 5m	R < 250m	2Ω > 23°	65	1
Totals				***5,487***	***100***

See also Appendix 1.2

Table 5 - Tunnel population by curvature

Within tunnels, 72% of the track is straight and 94% of track has a radius of curvature greater than 620 metres (straight or slightly curved). The curvature data came from a separate dataset so could not be cross-referenced to specific tunnels (Appendix 1.1).

3.3 Selection of representative tunnels for signal propagation loss comparison

Section 5 discusses principles behind the propagation of wireless RF signals through railway tunnels and how loss varies with distance into the tunnel. There are several attributes of tunnel design, construction, and alignment that contribute and influence the selection of representative tunnels used by the option selection process (Section 9):

- **Tunnel cross-sectional profile and size:** Generally, the larger the tunnel cross section, the greater the propagation range through the tunnel, and the smaller the blocking effect caused by the presence of the train (see Section 6.2). The option selection tool compares dual track with single track bores.

- **Tunnel lining:** The tunnel lining material, typically brick, rock, or concrete, have different electromagnetic characteristics and the quality of the finish (smooth or rough) will also affect refraction, reflection, diffraction, and absorption of RF signal that interacts with tunnel surfaces. The choice of lining and associated tunnel construction techniques also influences the standard cross-sectional profiles typical of the GB rail tunnel population (Section 3.2.4).

- **Tunnel curvature:** The curvature of tunnels will also affect signal propagation by increasing interaction of signal with tunnel surfaces.

The signal propagation behaviour of individual tunnels will vary because of many other differences. No tunnel will be the same size because of detailed design (emergency walkways, refuges, cross-passages and ventilation shafts, and the siting of other tunnel plant) as well construction tolerances and quality. All will vary by length. Real materials are rarely homogenous, so electromagnetic properties will vary throughout the tunnel as well as with temperature, humidity, and groundwater conditions.

This study originally selected eight tunnel types ‘T1’ to ‘T8’ to compare, representative of 80% of tunnels (Table 6). The remaining 20% are considered too difficult to assess without survey as they use multiple construction techniques throughout.

Type	Design/ Construction	Profile/ Size	Curvature/ alignment	Examples
T1	Brick or stone arch	Single track bore	Straight	Standedge (Old)* 1848 (alongside canal tunnels built by 1811 and operational dual track rail tunnel opened in 1871) 4,880 metres long
T2	Brick or stone arch	Single track bore	Curved	Marley Down Tunnel 1893, 890 metres
T3	Brick or stone arch	Dual track bore	Straight	Grimston (Leicestershire) 1878, 1,200 metres
T4	Brick or stone arch	Dual track bore	Curved	Dudley* 1852, 844 metres, • 805m radius curve from the North • straight from the South Copenhagen Tunnel (E)*, King’s Cross, 1886, 540m long
T5	Rock	Single track bore	Straight	Ffestiniog 1879, 3,530 metres
T6	Rock	Dual track bore	Straight	Box, broad gauge, 1841, 2.940 metres
T7	Concrete	Single track (circular segmental bore)	Slight curve	London Tunnel 2 (HS1) 2007, 10,000 metres
T8	Concrete	Dual track	Straight	North Downs (HS1) 2007, 3,200 metres

* Non-operational tunnels also tested by the study team

Table 6 - Tunnel Scenario categories considered

From a study perspective, and to address most tunnels currently in service today, or future tunnel designs, the study has focused on (a) tunnels constructed in brick (T1-T4) accounting for 70% of tunnels (constructed either by boring or ‘cut and cover’ up to 1900) and (b) concrete (T7-T8). Though the later only accounts for 3% of current GB tunnels, it is the material of choice for most new-build tunnels. The profile and regular surface geometry of segmental concrete tunnels also perform better as an RF waveguide (see Appendix 3.6 for information on propagation modes) compared with brick.

Whilst unlined hewn rock tunnels (T5-T6) offer contrasting materials and rougher surface quality it is the sole lining material for just 3% of tunnels, noting too that unlined rock is also used in some mixed construction tunnels.

Overall, 92% of all tunnel types are either single-track (T1-T2, T5, T7 – 69%) or dual track (T3-T4, T6, T8 – 23%).

Likewise, since 95% of tunnels are either straight (72%), or only slightly curved (22% with a minimum radius of curvature of 620 metres), the result of this categorization has allowed the options to be analysed (see Sections 7 to 9) to be reduced to just six tunnel types representing respectively single- and dual-track tunnels constructed of brick, unlined rock or concrete.

4 Wireless Connectivity within a Rail Environment

This section describes the fundamentals of wireless connectivity and the role of data links within tunnels.

The data link may be serving passenger mobile devices by direct connectivity to an MNO base station. This means the link will be affected by additional train shadowing, vehicle penetration, and body losses.

Alternatively, the data link may be acting as an intermediate signal 'relay' carrying the train-generated passenger traffic (connected for example via the on-train wifi service) by way of the on-train gateway and external train antenna.

The type of data link is important as it establishes the demand for data capacity and performance. Available capacity depends on the allocated signal bandwidth, the wireless technology standard and minimum target signal power level. Additional capacity and resilience can be augmented by techniques including MIMO antenna arrays, Carrier Aggregation of multiple allocated signal bands, and Dynamic Spectrum Sharing.

4.1 Direct or indirect connectivity to passenger devices?

Rail passengers expect to be able to enjoy the full benefits of connectivity from their MNO's network or via onboard wifi when travelling on trains just as anywhere else.

In practice, any tunnel wireless link is either providing direct connectivity from a mobile operator's base station to each passenger's wireless devices or, indirectly as an intermediate data link to an external train antenna and on-train gateway serving passenger devices (Figure 3).

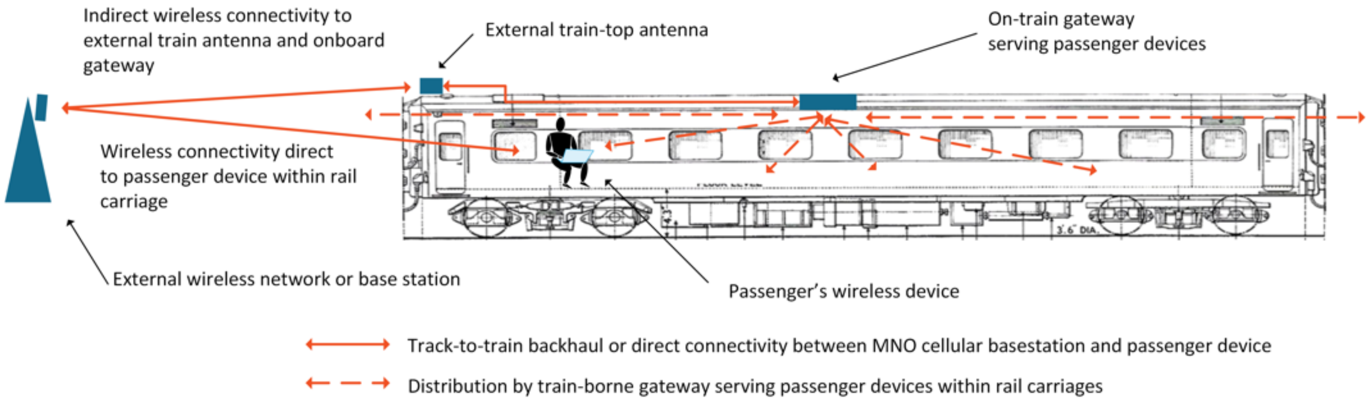


Figure 3 - Direct connectivity to passenger device versus indirect data link to external train antenna and on-train gateway

The tunnel wireless link must be able to meet the capacity requirements of either role.

Contrast with GSM-R Digital Cab Radio and ETCS Data-only radio (EDOR)
GB trains are already fitted with GSM-R Digital Cab radios (since 2012) and some with EDOR radios as part of cab-based European Train Control Signalling (ETCS) schemes. Both rely on 2G wireless data links (evolving from circuit to GPRS package switching) operating in the 900 MHz frequency band. This is provided by the dedicated Network Rail Fixed Telecommunications Network (FTN) designed to cover the GB mainline including deep cuttings and rail tunnels. Dedicated external train antennas are required to serve each cab radio or EDOR installation to achieve the high safety integrity requirements. However, data capacity requirements are modest.

4.2 Demand for passenger connectivity

The RF link budget ultimately determines the quality of service and data capacity (Mbps) the RF link can offer, whether for voice or data services, to individual mobile devices.

Forecasting voice and data throughput demand for a trainload of passengers is hard, but Ofcom and the DfT have made their own estimates and Transport Focus (TF) has monitored passenger traffic levels (Table 7).

Year	Type (Source)	Average Passenger Demand (Mbps)	Average Trainload Demand (Mbps)	Comments
2015	Growth (Ofcom)			800% demand increase 2011-2015 [1]
2016	wifi (DfT)	0.256	100	95% coverage of route, 85% of pax, 390 active users per train, 25% year-on-year growth in throughput [1]
2017	Voice (Ofcom)	-	-	Target 90% of 90 second voice calls are uninterrupted during journey
2017	wifi (Ofcom)	0.15	120	800 active users per train [7]
2019	3G/4G data (TF)	3.3	-	Average measured [4, 5]
2019	wifi data (TF)	1.4	-	Average measured [4, 5]
2019	Growth (Ofcom)	-	-	Target 2 Mbps consistent data rate per pax to browse/ view mobile video [4]
2025	3G/4G data (Ofcom)	1.5	1,200	Tenfold increase 2017-25 [7]

Table 7 - Forecast traffic demand trends for train-borne wireless connectivity

The table highlights that within the near term, RF link budget planning should target 1.5 Mbps per passenger device directly and 1.2 Gbps for whole train systems whether delivered through wifi or other train-borne gateways.

4.3 Capacity of wireless connectivity technologies

4.3.1 Technology, spectrum, and topology

The main technologies of current and emerging interest to wireless connectivity for rail passengers within this study include cellular, wifi, and proprietary millimetric wave (mmWave) (Figures 4 and 5).

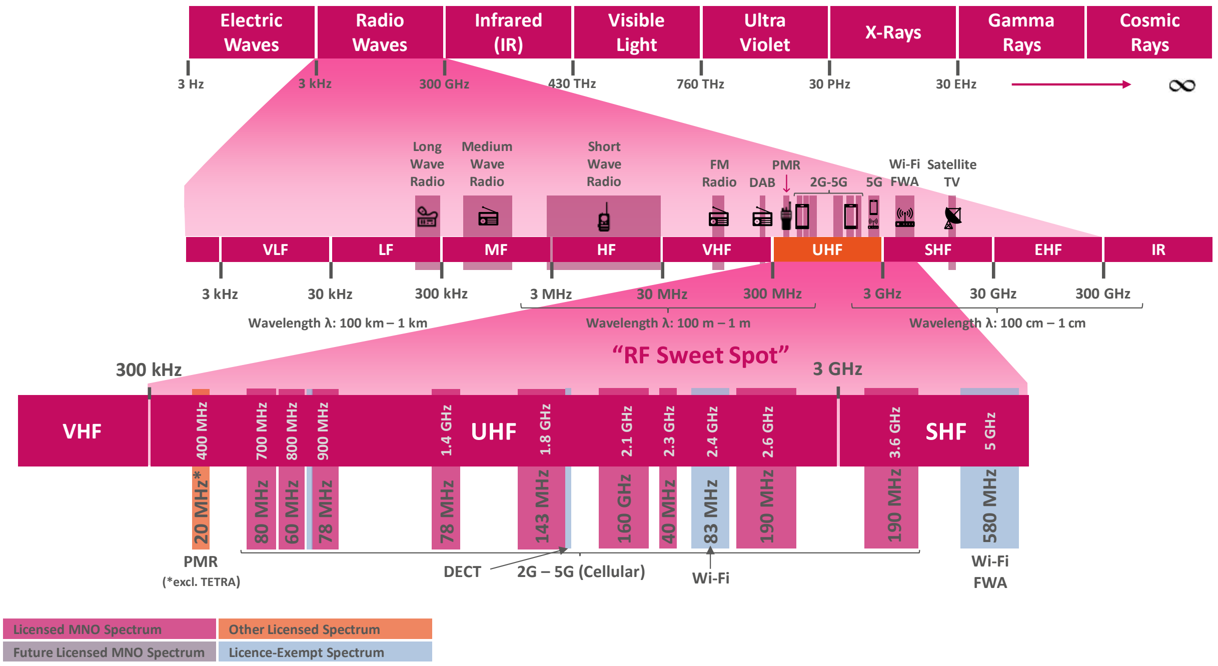
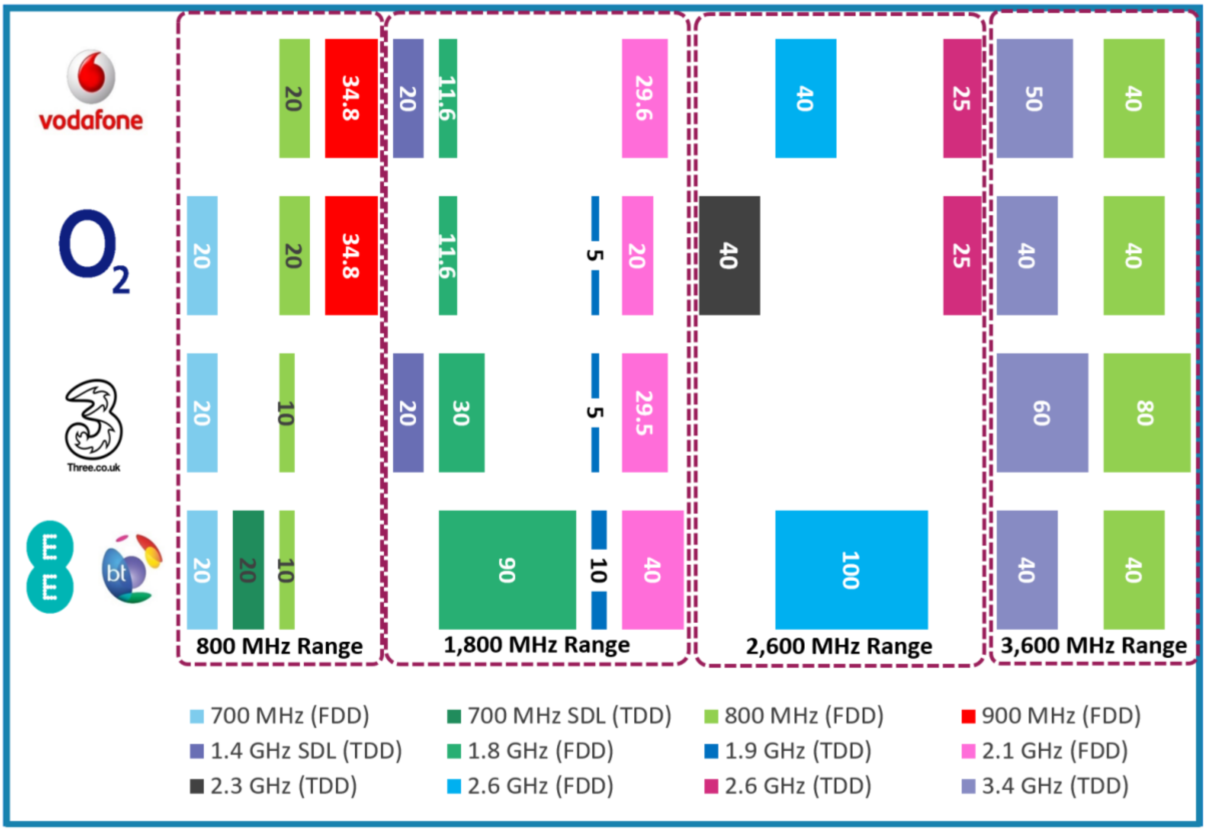


Figure 4 - Electromagnetic Spectrum (Source: Real Wireless)



The number within each box is channel signal bandwidth allocation (MHz)

Figure 5 - UK Spectrum Allocation to Cellular Mobile Network Operators 2021 (source: Ofcom)

Cellular technologies, usually provided by MNOs, are based on the 2G–5G standards and operate over a spectrum allocated between 700 and 3,800 MHz (3.8 GHz).

This study has concentrated on 4G and 5G, as only they offer the ability to serve the levels of passenger broadband demand described in the previous section. These choices in turn determine the target signal levels, spectrum ranges, and proposed architectures.

Both 4G and 5G are also able to provide voice services, for example, by Voice over LTE (VoLTE). At cellular frequencies, signals may be propagated using directional antennas or by radiating cables (Section 7). Direct connectivity to passenger devices is possible if the signal strength is sufficient to overcome losses caused by shadowing, vehicle penetration, and body losses associated with the train (Section 6.2).

Wifi and newly emerging mmWave technologies that tend to be based on proprietary technologies operate at carrier frequencies above 5 GHz. Earlier generations of wifi that operate at 2.4 GHz do not offer enough capacity. These technologies focus on high-capacity broadband services and rely, as already described in Section 4.1, on the wireless link to act as an indirect intermediate signal relay to an external train antenna and on-train gateway to serve passenger wireless devices. Effective signal propagation at these higher carrier frequencies requires a clear line of sight between transmitter and receiver. Such mmWave technology is also susceptible to high levels of signal absorption from atmospheric moisture and precipitation.

Section 5 and Appendix 3 discuss signal propagation principles relevant to wireless connectivity within railway tunnels.

4.3.2 Capacity enhancement – Multiple Input Multiple Output antenna arrays

Multiple-Input and Multiple-Output (MIMO) is a method used to increase the capacity of a radio link by using multiple transmit and receive antennas in a multipath environment, taking advantage of multipath propagation and increased spectral efficiency by combining uncorrelated signals within the same frequency band.

MIMO is already used to improve data rates and performance for wifi, 3G, 4G and 5G solutions and the order of MIMO (e.g., 2 x 2 MIMO = 2T2R) defines the number of transmit and receive antennas.

Another application of MIMO is to use dual cross-polarised antennas for line-of-sight (LOS) fixed wireless backhaul (microwave, mmWave or Fixed Wireless Access (FWA) to increase link throughput). LOS MIMO works by creating an artificial multi-path by deliberate separation of antennas.

For example, a 2T2R LOS MIMO microwave link comprises two transmitters and receivers connected to two antennas at each end of the link. Each MIMO combination of transmitter and receiver (and associated antennas) can also be combined with established dual polarisation techniques to increase spectral efficiency and link capacities. While this technique works for LOS applications (Appendix 3.4 suggests that tunnel surfaces will impose additional signal polarisation and phase changes by the Brewster effect) it may not work well within longer tunnels.

4.3.3 Single channel data capacity

Table 8 shows the minimum single channel capacities that could be achieved with a minimum tunnel signal level of -105 dBm at a wide range of frequencies from 800 MHz to 67 GHz and covering MNO cellular carrier frequencies, Wifi and mmWave for typical signal bands, technology configurations and including 2x2 MIMO.

Technology	Carrier Frequency (MHz)	Wave-length (mm)	Signal Bandwidth (MHz)	Duplex	MIMO	Target Signal Level (dBm)	Minimum (Peak) Data Rate (Mbps)
Cellular 4G/5G	800	375	2 x 10	FDD	2T2R	-105	26 (60)
Cellular 4G/5G	1,800	167	2 x 20	FDD	2T2R	-105	52 (120)
Cellular 4G/5G	2,600	115	2 x 20	FDD	2T2R	-105	52 (120)
Cellular 4G/5G	3,600	83	1 x 40	TDD	2T2R	-105	93 (220)
Wifi	5,500	55	1 x 80	TDD	2T2R	- 90	220 (500)
mmWave	26,000	11.5	1 x 200	TDD	2T2R	-105	450 (1,000)
mmWave	60,000	5	1 x 2,160	TDD	2T2R	- 65	660 (1,500)

Note: -105 dBm RSRP corresponds to approximately 30% of the maximum spectral efficiency that can be achieved [8]

Table 8 - Achievable data rates by target signal strength

The ‘peak’ data rates stated in Table 8 are indicative of what could be achieved in an ideal scenario.

The achievable data rate reduces with minimum available signal level. For this study we have set a minimum signal level within a tunnel for cellular services at -105 dBm (RSRP – see box below). This level aligns with the JOTS’ [8] “Indoor for medium data rate” services level where approximately 30% of the theoretical peak data rate can be achieved.

The same approach was taken for wifi and mmWave services, where a target signal level was selected and expected to provide approximately 30% of the peak data rate. Both minimum and peak data rates are provided to indicate the expected range. Minimum signal levels will only be experienced for the short periods a train (with passengers) is traversing the area at the extremities of the cell. The implications of additional train losses on direct passenger connectivity are discussed in Section 6.2, with further details in Appendix 3.3.2 and Table 46.

Signal Power Metrics
Progressive evolutions of wireless technology generations have refined how signal level is measured. 2G used basic received signal level (RXLev). 3G introduced Received Signal Code Power of the Code Pilot Channel (RSPC CPiCH). 4G/ 5G have settled on Reference Signal Received Power (RSRP) which reflect the fraction of signal power containing control signals relating to cell handover and the decoding of the embedded data. This difference in signal measurement definition and practice is why 2G signal strength indicator requirements appear to be much higher than 3G/ 4G/ 5G, typically 20 dB more.

The signal power level is measured in units of dBm (see box).

Why is dB used to compare signal levels and what does dBm mean?
Since sound and RF signals vary so widely in strength, they are measured using a logarithmic scale. The decibel is simply a measure of relative strength between two signals where 0 dB means no difference, +10 dB means 10 times greater, +20 dB 100 times greater and so on. -10 dB means a signal 1/10th of the reference signal, -20 dB is 1/100th of the reference. Remember that logarithms also apply between 1 and 10. -3dB means the signal is ½ or 50% of the reference, whereas -6 dB is a ¼ or 25%.

So, a range of signal attenuation between -3 dB and -30 dB is a wide range from ½ (50%) of the reference signal down to 1/1000 (0.1%).

The dB scale can also be used to show absolute signal power levels if referenced against a common datum, usually 1 milliWatt. So, if 1 milliWatt = 0 dBm, then 0.1mW = 1mW/10 = 0 dBm - 10dB = -10 dBm.

Signal strength tends to decrease steadily but non-linearly from a point source. For example, a signal decaying inversely with range reduces by -3 dB per octave* each time the distance doubles, and a signal decaying inversely with the square of range would reduce by -6 dB as the range doubles. Such characteristics would appear as straight lines if plotted on a logarithmic dB versus ***log*** range ($\log_{10}$ metres) chart. A slope of -10dB per decade* would indicate a signal decaying inversely with range, and a slope of -20 dB/decade for a signal decaying inversely with the square of range.

Signals that decay exponentially would have a loss characteristic that would appear as a straight line on a logarithmic dB versus ***linear*** distance range (metres).

* *Decade means per tenfold increase. So, the same change in loss, say -10 dB, would occur between 1 metre and 10 metres and between 10 metres and 100 metres, 30 metres and 300 metres and so on.*
Octave means a twofold increase in distance and comes from music where an increase in pitch by an octave requires a doubling of the sound frequency.

4.3.4 Capacity enhancement – carrier aggregation

Cellular single signal bandwidth channels (Table 8) offer data rates below 100 Mbps. However, 4G/5G technologies include provision for Carrier Aggregation (CA) to aggregate multiple channels.

MNOs such as EE have already aggregated three carriers at some locations to offer higher throughput LTE/ 4G services (2 x 20 MHz at 1800 MHz plus 1 x 10 MHz at 2100 MHz) to achieve an overall bandwidth equivalent to 2 x 50 MHz aggregated FDD (uplink and downlink). Available carrier aggregation configurations and bandwidths are recorded in 3GPP Technical Standards as they are offered and tested, often because of lobbying by the MNOs.

Base station and transceiver antennas must also be configured to work with all the relevant channel bandwidths for Carrier Aggregation to be implemented.

4.3.5 Capacity enhancement – Dynamic Spectrum Sharing

Dynamic Spectrum Sharing (DSS) is an emerging technique, enabling 4G and 5G co-existence and efficiencies in spectrum usage. It is a technology that allows the simultaneous use of 4G and 5G in the same frequency band.

This spectrum sharing of 4G and 5G technologies enables the swift rollout and expansion of 5G whilst still supporting 4G and therefore 4G-only devices. DSS brings the benefit of 4G spectrum usage for 5G without having to reform 4G spectrum or acquire new 5G spectrum and provides the statistical efficiency benefit of spectrum resource sharing across two technologies.

4.3.6 Dynamic capacity optimisation

Dynamic capacity optimisation techniques can be used to adapt to changing characteristics of each radio link. Wireless signal propagation of fixed links may be affected by changes over weeks or months, such as the growth of forests or snow cover of mountainous areas. Atmospheric moisture and precipitation will increase the losses of even short-range millimetric wave links through signal absorption. Techniques used include:

- **Automatic Transmit Power Control** (ATPC) monitors the signal at the receiver and boosts the transmitter power to compensate.

- **Adaptive Coding and Modulation** (ACM) monitors the signal to noise ratios and bit error rate at the receiver and adapts the modulation and coding scheme protocol to trade throughput (capacity) for a reduced error rate.

These techniques only work well if considered as part of the original link design by radio planning engineers to anticipate and tolerate foreseeable abnormal or evolving operating conditions.

4.3.7 RF test frequencies

RF testing and modelling during this study has covered the spectrum between 700 and 5,500 MHz to cover the conventional 2G (GSM), 3G (UMTS), 4G (LTE) 5G (NR) and wifi frequencies. Emerging mmWave technologies have been assessed at nominal 26 and 60 GHz spectra.

Test propagation measurements were made at continuous wave spot frequencies across these spectra, subject to test licence conditions and test equipment available. The spot frequencies used were:

- 890 MHz
- 1,801 MHz
- 2,590 MHz
- 3,510 MHz
- 5,500 MHz
- 26,000 MHz
- 58,320 MHz

See Section 7.5 and Appendix 4 for more details.

5 RF signal propagation principles and rail tunnels

This section outlines electromagnetic principles of signal propagation to explain the typical signal propagation logarithmic loss (in dB) versus range (in metres) characteristics of real railway tunnels.

Reconciling theory with practice
This is primarily an engineering study extending wireless knowledge for practical application to rail tunnels. However, the study team has found that predictions made by an extensive body of theoretical and academic studies since the 1970s are not necessarily consistent with measurement in the field (Section 7.5 and Appendix 4). This section offers a short and broad qualitative overview of signal propagation principles to provide plausible, if not definitive, explanations for the observed test results.

It provides qualitative support for assumptions made where predictive modelling is constrained by the lack of detailed data about tunnel configuration and material properties. While the propagation of all electromagnetic radiation is defined by Maxwell's equations (see box below) and may be applied to rail tunnels as lossy dielectric waveguides, useful insights can be gained by reference to earlier concepts of rays, refraction, diffraction, absorption and polarisation.

James Clerk Maxwell's Equations of 1873 [9]
By postulating that a time-varying 'displacement current' must be able to flow in insulating (dielectric) materials, Maxwell was able to use vector calculus to define a set of equations that unified previous electromagnetic theories of electrostatics and magnetism and predicted the propagation of electromagnetic radiation across the full electromagnetic spectrum, both through free space and other forms of waveguide.

This wave-based theory later proved consistent with special relativity if not the 'light as a particle' (photon) behaviours explained by quantum mechanics. In vector calculus form Maxwell's equations take the form:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla . \mathbf{D} = \rho \qquad \nabla . \mathbf{B} = 0$$

$$\mathbf{D} = \varepsilon \mathbf{E} \qquad \mathbf{B} = \mu \mathbf{H} \qquad \mathbf{F} = \mathrm{q}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \mathbf{J} = \sigma \mathbf{E}$$

Vector variables are **bold**, scalar variables plain.
Vector calculus operators: $\times$ cross product $\nabla \times$ (curl) $\nabla .$ (divergence)

H is magnetic field strength, **B** is magnetic flux density, **J** is current density, **E** is electric field strength, **D** is electric flux density, **F** is force and **v** is velocity of the moving charge. And:
$\varepsilon = \varepsilon_r \varepsilon_0$, where ε is the absolute permittivity of a material expressed relative to the permittivity of free space, ε_r is the relative permittivity a dimensionless unit and $\varepsilon_0 = 8.854 \times 10^{-12}$ Fm^{-1} is the electric constant (in Farads per metre)
$\mu = \mu_r \mu_0$, where μ is the permeability of a material expressed relative to the permeability of free space, μ_r is the relative permeability a dimensionless unit and $\mu_0 = 4\pi \times 10^{-7}$ Hm^{-1} the permeability constant (in Henries per metre)
$\varepsilon_0 \mu_0 = 1/c^2$, where c is the speed of light within a vacuum 2.998×10^8 ms^{-1}
σ = conductivity (AV^{-1}m^{-1})

Maxwell's equations define all principles relevant to wireless signal propagation. However, they are difficult to solve in the real world with materials that are not uniform and vary with atmospheric moisture and seasonal variations in ground water conditions. Also, every railway tunnel is unique, constructed from different materials or hewn directly from local rock formations. They vary in alignment, cross-sectional shape, size, and surface quality.

The RF test results presented in Appendix 4 confirm that RF signal is attenuated strongly and erratically with distance into each tunnel and that the behaviour varies with carrier frequency.

Section 5.1 explains why taking a broader view of the signal propagation problem and combining alternative theories may help explain the RF measurements from the field. Supplementary information may be found in Appendix 3.

Section 5.2 applies these principles to explain a typical signal propagation loss characteristic. Many of these principles were discovered long before Maxwell but offer helpful insights into specific phenomena. Many were discovered while considering the optical properties of visible light or the progress of ripples and waves on the surface of water. Other concepts arise directly from analysis of Maxwell's equations, particularly the theory of antennas, the existence of the full electromagnetic spectrum, the importance of polarisation, and how waves propagate through waveguides differently from free space.

The sources used include general textbooks [10] or handbooks [11] and more specialised works [12, 13, 14]. A wide range of international studies were considered since the mid-1970s [15-40].

5.1 Signal propagation loss – a broader view consistent with RF field measurements

Radio planning engineers need to know how to propagate a wireless signal from transmitter to receiver antenna. The simplest direct transmission medium is through free space (vacuum). Transmission directly through atmospheric air at ground level is very similar except for signal absorption by atmospheric moisture or resonant absorption by oxygen specific frequencies (particularly the millimetre waveband).

When it comes to railway tunnels, signals may travel as if through free space if tunnel surfaces are too far away to interact with the signal in ways that are detected by the receiver. However, if the tunnel surfaces are close enough to affect signal transmission, the tunnel must be treated as a form of electromagnetic waveguide.

Wireless transmission becomes more complex with the need to understand not only what is happening at the tunnel surface but also the more complex interaction of transmit and receive antennas that couple signal into and out of the finite number of propagation modes supported by the waveguide.

It may be helpful to treat signal propagation loss as a combination of different mechanisms, each of which depends differently on carrier frequency/ wavelength and distance and are consistent with RF measurements:

- **Consider if the tunnel affects signal propagation at all.** This will be true if the tunnel cross-section is very large relative to the carrier wavelength (approximately 1,000 wavelengths), such as at mmWave frequencies directed line-of-sight rather than at tunnel surfaces.

  Even if there is a tunnel surface interaction, only negligible levels may travel an equivalent distance back to the receiver. This may also be true close to antennas even at cellular frequencies (700 MHz to 3,600 MHz) when any Fresnel zones are small [11] (Appendix 3.4). Any signal will also interact with tunnel surfaces if directed at them whether by the alignment of antennas or the changes in horizontal and vertical curvature, changes in tunnel cross-section or the presence of other obstacles.

- **Propagation through free space.** Signal power density decays inversely with the square of distance (Appendix 3.3). The Free Space Path Loss (FSPL) curve is always the same shape (for example see Figures 41 and 44) but varies up and down according to wavelength (Table 44) because the transmission efficiency of a free space antenna increases with the square of wavelength. So, the propagation loss of an efficient antenna at 800 MHz will 13 dB less than at 3,800 MHz and 37 dB less than at 60 GHz.

- **Coupling signal into the lossy tunnel waveguide to activate multiple modes that leak by refraction and transmission into the tunnel walls.** A directional antenna at a tunnel portal becomes a component of the tunnel as a waveguide and excites a finite number of modes to propagate into the tunnel. An antenna away from the portal will transmit into free space and a diffuse wavefront will arrive at the tunnel portal and couple a different mix of propagation modes.

  Similarly, the receive antenna on a passenger device or fitted to the train will only receive signal power from local modes that couple into it. The receiver does collect all energy present across the face of the tunnel. Each propagating mode travels at different speeds and their signal decays exponentially with distance. Each mode decays at a different rate dependent on tunnel surface cross-section, properties [41, 42, 43] and roughness that may vary along the length of the tunnel, as will the tunnel profile. Modes are less affected by surface roughness (less than $\lambda/10$) [10] at lower frequencies but propagate more efficiently at higher frequencies.

The total signal power propagating through the tunnel must decay monotonically. The rate of detected signal propagation loss will be somewhere between that of free space loss and exponential decay. Some theories suggest a clear 'break point' distance [19] where most modes will have decayed. Study measurements have not observed such an abrupt change in loss characteristic. However, it is interesting that the 'break point' distance also corresponds to the location where the first Fresnel zone has grown to the same size as the tunnel. The 'break point' distance may be more helpful simply as a relative indicator of strong or weak coupling between antenna and tunnel as waveguide.

- **Persistence of a residue of lower order modes deeper into the tunnel.** Some of the lower order modes persist, like rays that skim the tunnel surface almost parallel to the tunnel axis, reflecting more strongly. These will continue to decay exponentially and appear as shallow straight lines on logarithmic signal propagation loss (in dB) versus linear distance (in metres). The rate of decay should be lower at higher frequencies unless undermined by surface roughness scattering into lossier higher modes [10].

  Some test results report a sudden reduction in loss that persists along the tunnel. For example, Figure 51 shows a sudden reduction and shift in loss of 10 dB at 1,800 MHz 1.2 km into Standedge Old single-track tunnel. One explanation would be a sudden change in position or orientation of the receiver coupling into more of the modes still present at that point in the tunnel.

- **Multiple fading mechanisms**. Many theories predict a sudden fall off in signal fading beyond a certain range. Test results suggest far more gradual changes in erratic fading behaviours and none that align with predicted 'break point' distances. It seems wiser to assume that a much wider mix of fading mechanisms is at play. They are all linked to Huygens' principle of propagation by constant re-diffraction of wavelets that may interfere constructively and destructively in multiple ways [11] (Appendix 3.2).

  Such interference phenomena are affected by so many variables suggests that precise modelling of fading behaviour is very difficult, except possibly for the smoothest and most regular tunnels. Even then, each case would be for transmitter and receiver at precise locations that will not happen for passengers at different locations on moving and swaying trains, Wireless modulation and coding schemes and MIMO techniques also reduce the effects of fading further.

Table 9 summarises the many potential mechanisms involved and how they vary with carrier wave frequency or wavelength and distance into the tunnel. More detailed information is presented in Appendix 3:

- Appendix 3.1 **RF Wireless Propagation as rays** to explain reflection and refraction at a boundary of two transparent materials (**Snell's Law**), since **the refractive index** of railway tunnel wall materials is typically in the range 2 to 3.5 and sometimes more.

- Appendix 3.2 **Huygens' principle** of propagation by constant re-diffraction of wavelets to explain **diffraction** at sharp edges and **signal fading** caused by constructive and destructive interference between phase-shifted waves.

- Appendix 3.3 the **Friis transmission formula** for line-of-sight propagation in free space and its dependence on wavelength and distance (**inverse square law**).

- Appendix 3.4 **Fresnel zones** – applying Huygens' principle to understand how close an obstruction such as a tunnel surface must come to disturb propagation through free space at a given wavelength - the lower the frequency (longer the wavelength), the more likely an interaction.

- Appendix 3.5 the impact of **polarisation** on reflectance (**Brewster Angle**) at tunnel surfaces - tunnel surface geometry may determine the polarisation of propagated signal more than the source transmitter that may affect some MIMO configurations (section 4.3.2).

- Appendix 3.6 three typical **waveguide** designs, none directly applicable to rail tunnels, but a useful introduction to propagation '**modes**', modal attenuation, signal fading by inter-modal signal mixing, and the threat of multi-modal signal dispersion.

- Appendix 3.7 about **diffuse reflection** caused by signal scatter from **random variations** in the alignment, geometry and material properties of tunnel walls, including small amounts of **energy absorption** and **thermal losses** caused by **electrical conduction.**

- Appendix 3.8 **Antennas** as Maxwellian waveguide and coupling components.

Reference	Phenomenon	Dependency Wavelength λ	Dependency Distance d	Application to tunnel propagation
App3.3	Free space path loss (FSPL)	Size of tunnel (wavelengths)		Occurs where signal TX-RX path has minimal interaction with tunnel surfaces: • Near antenna where Fresnel zones are too small to reach tunnel surfaces • At high frequencies since tunnel space is enormous (approximately 1,000λ)
App3.3.1	FSPL antenna efficiency	proportionate to: λ^2 ($\propto \lambda^2$)		Much smaller propagation loss at lower frequencies if FSPL applies, including close to the antenna.
App3.3	Free space path loss (antenna range)		$\propto 1/d^2$	Good indicator of FSPL performance
App3.3.2& Section 6.2	Free space path loss (as proxy for range reduction)		$\propto 1/d^2$	Estimates reduction in usable signal range caused by additional train losses.
App3.2	Huygens' diffraction	Yes	Yes	Spacing of all signal fading effects across the face and length of the tunnel caused by constructive and destructive interference of wave fronts.
App3.4	Fresnel zone diameter	$\propto \sqrt{\lambda}$	$\propto \sqrt{d}$	Expands along tunnel faster at lower frequencies to interact with tunnel surfaces sooner. This may explain earlier signal fading at lower frequencies.
App3.6	Propagation Loss along leaky dielectric waveguide	$\propto \lambda^2$	Exponential decay	Individual modes decay exponentially with distance (linearly on log loss (dB) versus distance chart). Higher frequencies propagate further.
App3.8	Antenna efficiency – waveguide coupling	Yes	Yes, and location across face of tunnel.	Must expect different behaviour from free space. Also, directional antenna receivers only detect local signal power, not all the energy reaching that point in the tunnel. Received power will be affected by location of receiver across tunnel face and local signal fading effects.
App3.1	Tunnel surface optical properties	Slightly	Yes	Values will vary by mode and local variation in material along the tunnel and humidity.
App3.7	Roughness	$\propto 1/\lambda$	Yes	Higher frequencies affected by small scale variations on tunnel surface variations.
Section 4.3	Atmospheric moisture	Yes		Especially at mmWave frequencies, based on signal absorption spectrum of oxygen.
App3.5	Signal polarisation	Slightly	Yes	The longer the tunnel the bigger the impact of tunnel surfaces on signal polarisation

Table 9 - Factors affecting signal propagation

Section 5.2 illustrates how these mechanisms combine to influence the signal propagation loss characteristic with distance into the tunnel.

5.2 Application to typical signal propagation loss characteristic

Figure 6 illustrates a typical measured signal propagation loss characteristic for directional antennas to show how the mechanisms described in Section 5.1 may combine.

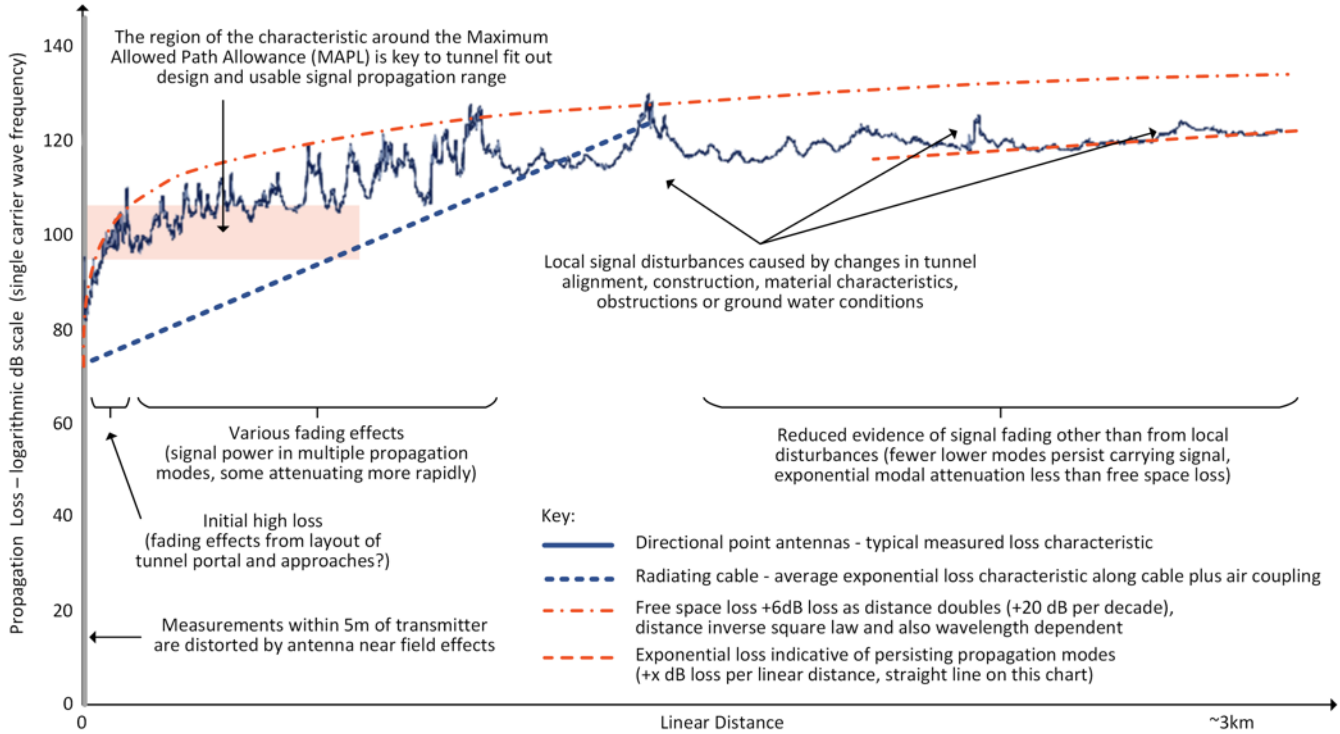


Figure 6 - Typical tunnel signal propagation loss characteristic

The chart plots logarithmic loss (in dB) versus linear distance into the tunnel from the portal. For wireless connectivity applications the region of the characteristic where signal propagation loss reaches the Maximum Allowed Path Loss (MAPL) is crucial (see Figure 14). If the loss is less than MAPL then the target minimum data rate can be achieved whatever the characteristic, if the loss is more than MAPL then the target minimum data rate cannot be achieved.

Three reference curves are shown. The free space loss characteristic shows a steep initial rise in loss and the signal will follow this standard curve if there is little interaction between signal and tunnel surfaces. Free space signal loss increases by 6 dB for every doubling of distance (20 dB per decade, as distance increases by a factor of ten). One wavelength-dependent reference data pair (reference loss in dB and distance) is also needed to fix the height of the curve on the chart, typically set at a distance of 1 metre (Appendix 3.3.1, Table 44).

In practice, measurements within 5 metre of a test transmitter will be unpredictable because of ‘near field’ effects. If the tunnel does interact with the signal and behaves as a lossy waveguide, many propagating modes will be generated. As can be seen in Figure 6 the signal varies erratically with increasing distance into the tunnel because of the various fading mechanisms at work.

The higher propagation modes are attenuated more quickly by refraction into the tunnel walls and at a rate that depends strongly on the characteristics of the tunnel and the signal wavelength. The impact of rapid signal fading reduces with distance into the tunnel as only the lower propagation modes can persist for longer distances. Even these will attenuate exponentially with distance (a shallow straight line on a dB versus km chart as illustrated by the second reference dotted line). However, signal will continue to be erratic, especially if there are sudden local disturbances caused by changes to tunnel cross section, alignment, lining material, ground conditions, or other obstacles.

All disturbances can create new standing waves from reflected and diffracted waves or affect the mix of modes detected by the receiver. Any changes in receiver alignment while measuring the characteristic will also affect the detected loss.

The third (straight blue dotted) curve illustrates the typical average loss characteristic of the alternative signal distribution technology using radiating cables. Signal propagation is radial to the axis of the cable to cover the local tunnel cross section. The loss is a combination of losses within the radiating cable that increase exponentially with distance along the cable plus ‘air gap’ coupling losses between the cable and the target receive antenna, itself likely to be operating in the antenna’s near field. Manufacturers issue empirical data to specify average coupling losses at different distances from the cable (typically 2 metres and 5 metres).

The use of both directional antennas and radiating cables for practical tunnel fitment application designs is described in more detail in Sections 7 and 8.

6 Route deployment and railway operations

This section looks at the practical aspects of improving mobile connections within tunnels, and wider system aspects, including the additional propagation losses caused by and within trains, the potential need for additional onboard equipment and roof-top or front-of train mounted antennas to manage cell handovers to maintain uninterrupted connectivity.

In brief it also looks at the vulnerability of mmWave frequencies to additional absorption losses from atmospheric moisture and precipitation.

6.1 Length of tunnels requiring wireless signal improvement

The length of tunnel that justifies fitting an in-tunnel wireless solution depends on several factors including the existing tunnel entrance and surrounding local area coverage from existing MNO basestation sites, the duration of the signal and connection dropout that passenger devices can tolerate, and what may be considered economically reasonable.

Practically, and understandably, tunnels are hard to address particularly as MNOs' macro sites are rarely planned and optimised for railway coverage. Even if there is general coverage of the open track, the tunnel portal may be within the shadow of the deep tunnel approach cuttings and at an oblique angle to the signal source. In such cases, signal can fall below usable levels just a few metres into the tunnel. In contrast, signals entering directly into short tunnels with large cross-sections may penetrate tens of metres to the end of the tunnel.

In practice, trains and their passengers speed through tunnels as they use their wireless devices and may only lose signal for short periods of time. Likewise, many applications and device technologies offer built-in resilience to transient connection losses.

Table 10 shows the distance covered by trains for different time intervals and at different line speeds. For example, if a connection can cope with the loss of signal for up to 5 seconds, in that time a train travelling at 50mph will have travelled 115 metres, but 280 metres on a 125 mph express train and 420 metres for a very high-speed train.

Train speed (mph)	Train Speed (km/h)	Equivalent metres / second (m/s)	Distance travelled within 1s (metres)	within 3 seconds (metres)	within 5 seconds (metres)
50	80	22	22	66	115
75	121	34	34	100	170
100	161	45	45	135	225
125	201	56	56	170	280
140	225	63	63	190	315
186	300	83	83	250	420

Table 10 - Distance travelled by trains over short intervals (cell handover)

By corollary, since the maximum length of GB passenger trains is 240 metres, some part of a train will always be outside of any tunnel less than approximately 250 metres long, and no passenger should lose signal for more than 5 seconds on any train travelling at over 100 mph – though exceptions could include tunnels in urban settings on congested lines where large numbers of passenger voice calls or video traffic could be disrupted as trains run slowly or are held at signals.

This study therefore assumes that tunnels shorter than 250 metres do not merit dedicated wireless infrastructure unless demonstrated by detailed operational and economic assessment, noting too that tunnels that are less than 250 metres long account for half of GB rail tunnels (Table 3).

6.2 Signal propagation losses caused by the train

Wireless connectivity for the passenger is also affected by the network function of the wireless link within the tunnel. For direct links to passenger devices, the signal will also incur additional losses (Figure 7) caused by a combination of train shadowing [18], vehicle penetration loss, body losses caused by the passenger user and crowding losses from the presence of other passengers and their belongings [6].

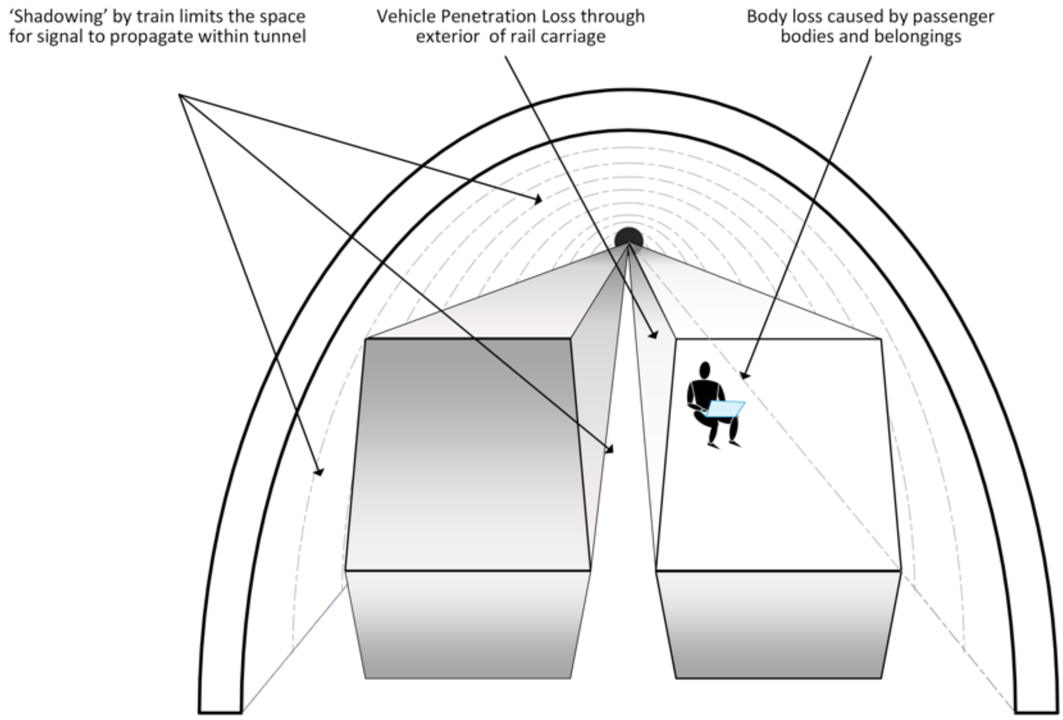


Figure 7 - Additional train losses affecting direct connectivity to passenger devices

Signals will need to propagate through the reduced space within the tunnel caused by the 'shadowing' presence of the passenger-carrying train. Shadowing becomes even worse if another train passes within a dual track tunnel or within a single bore tunnel with tight clearances.

Additional losses will also arise from vehicle penetration loss, caused by the design of the train, and the effects of the passengers themselves and how crowded the train may be.

Wireless signals can only propagate with no attenuation through mediums that are dielectrically transparent such as (unmetallized) bodyside windows and gaps caused by doorways and any ventilation or service ducts. These losses are less for passengers seated next to windows, while signals to other passengers will be further attenuated by the metallic skin of the train and other fixtures and fittings.

User body loss is caused by the passenger's use of their device. Passengers may block signals with their bodies disrupting the function of the built-in antenna and receiver electronics. Separately, crowding body loss is caused by the presence of other passengers and their belongings.

Table 11 shows how variable these losses can be, and the assumptions used in preparing the range lookup tables in Section 7.6 as part of option selection described in Section 9.

Loss Mechanism	Potential Variability	Assumptions Dual Track All frequencies (dB)	(Radiating Cable) Single Track bore 800 MHz	Single Track bore 1,800 – 3,600 MHz
Train Shadowing (single train)	0 to 30 dB	-	-	-
Vehicle Penetration Loss	3 to >30 dB	10 dB	15 dB	20 dB
User Body Loss	2 to 20 dB	5 dB	5 dB	5 dB
Crowding Body Loss	0 to 60 dB	-	-	-

Table 11 - Additional Train Loss Assumptions for direct connectivity (source: [6])

6.3 Train shadowing of external train antennas

An external train antenna serving an on-train gateway (such as today's on-train wifi systems) will receive and re-purpose the local tunnel signal to passenger devices on the train, and in theory be less susceptible to train shadowing and the other losses. However, some train shadowing loss may be unavoidable if the external train antenna cannot be fitted directly to the ends of trains (Table 12).

For mmWave technologies line of sight connectivity is essential.

Wireless Technology		Preferred Mounting Location	Train Shadowing Loss Allowance
Cellular	800 – 3,600 MHz	Anywhere along roof of end carriages (height 4.5m).	3 dB
wifi	5,500 MHz	No more than half a train carriage from train ends on the roof (height 4.5 metres).	0 dB
mmWave	above 26 GHz	On the end or nose or end carriage to allow forward- or backward- facing line of site operation.	0 dB

Table 12 - Train shadowing losses affecting external train antennas

6.4 Additional On-train gateway equipment

On-train gateways will be essential to applications of line-of-sight wifi and mmWave solutions operating at frequencies greater than 5 GHz to minimise the train losses described in Section 6.2. Equipment to be installed on trains will comprise three main components:

- A train-borne antenna is installed on the top of the train, ideally near the end of the train. The antenna receives and transmits signals to and from the trackside installation and is connected to the on-train gateway.
- The on-train gateway receives the signal from the external antenna and translates the transmitted payload into data that can be transmitted over an IP network.
- The onboard connectivity solution is typically based on wifi access points in each of the couches, that are connected to the on-train gateway but could be developed as a technology agnostic gateway.

Further assessment of these systems is beyond the scope of this study but as been discussed elsewhere [6].

6.5 Cell Handover

MNO cellular networks rely on progressive handover of control between MNO network cells. Any tunnel fitment solution needs to comprise pairs of back-to-back antennas to ensure cell overlays beyond the tunnels and within and sufficient overlap between adjacent cells to guarantee seamless handover (Figure 8).

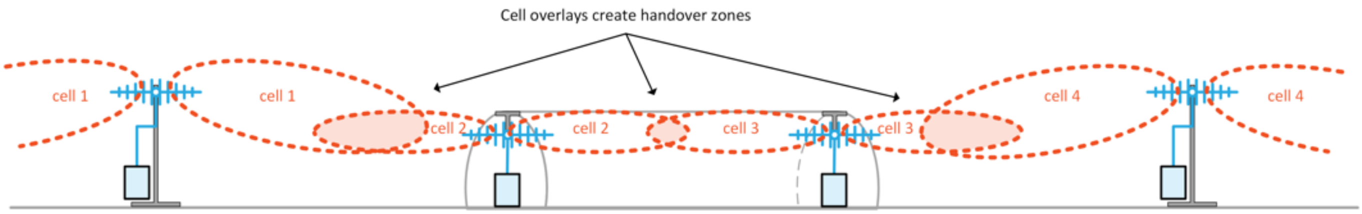


Figure 8 - Outward pointing antennas to facilitate cell handover

The length of cell overlay needs to be long enough to allow handover to complete within a 5 second window, approximately 300 metres at a maximum line speed of 125mph but may be calculated with reference to Table 10.

Coverage within the tunnel needs to extend beyond the far portal to support cell handovers so may also require an additional outward facing antenna.

The antenna pointing away from the tunnel entrance (in a near-portal or portal scenario) can be mounted higher above the railway track to optimise line of sight coverage. Figure 9 shows how data capacity decreases with distance under ideal conditions from a 4G/ 5G outward facing antenna.

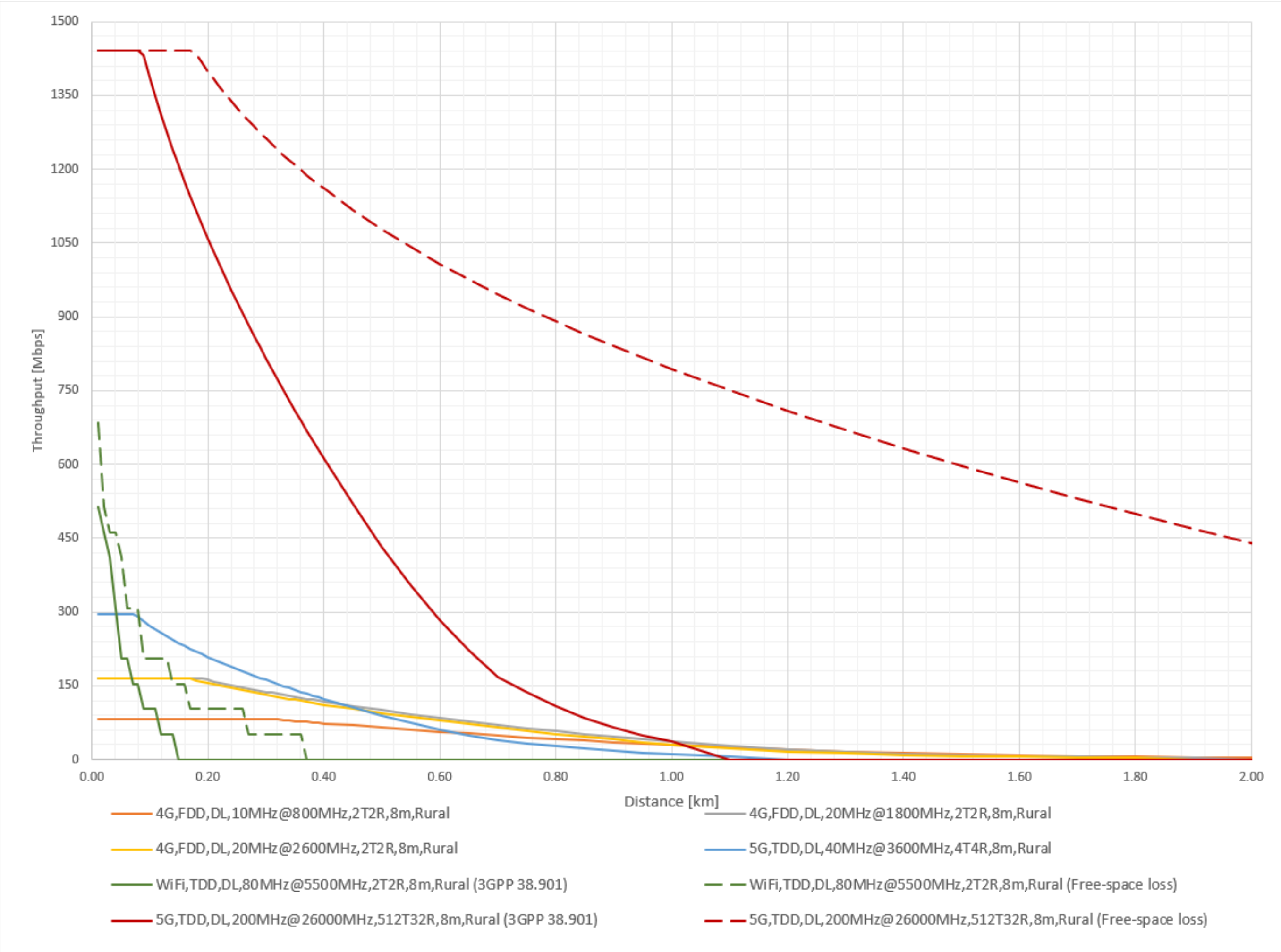


Figure 3 - Variation of data capacity by range for outward pointing antenna (source Real Wireless)

In-tunnel antennas simply used to extend the same cell do not need to allow for cell handover. Handovers for wifi and mmWave solutions may be more tightly controlled and completed within 1 second.

7 'Blueprint' propagation architectures and expected usable range

This section introduces the application design options available to fit railway tunnels with wireless connectivity. Tunnel fitment designs are based on the application of standard 'blueprint' architecture elements.

Each 'blueprint' architecture element considers alternative antenna and fronthaul component placement options. They also compare antenna technologies, either directional antennas or distributed radiating cables.

All 'blueprint' element designs support cell handover as part of route deployment (see Section 6.5). They also assume that competing MNOs supply their own base stations and remote radio units to amplify signals, whereas railway constraints often force them to share the same passive antenna or radiating cable components [8].

This section also describes how the usable range of each antenna technology depends on signal propagation loss within the tunnel. However, the usable range is also constrained by the data link power budget and the Maximum Allowed Path Loss (MAPL) that can be tolerated to achieve minimum tunnel signal power targets (see box).

Modelling assumptions and signal propagation test results are used to populate signal range lookup tables for both direct connectivity or indirect on-train gateway solutions for each of the eight standard tunnel types, blueprint architectures, and carrier frequencies. Some options will be ruled out immediately because of low signal range. The signal range lookup tables will be used as part of a wider option comparison within Section 9.

7.1 Candidate 'Blueprint' architecture elements for propagation

7.1.1 Overview

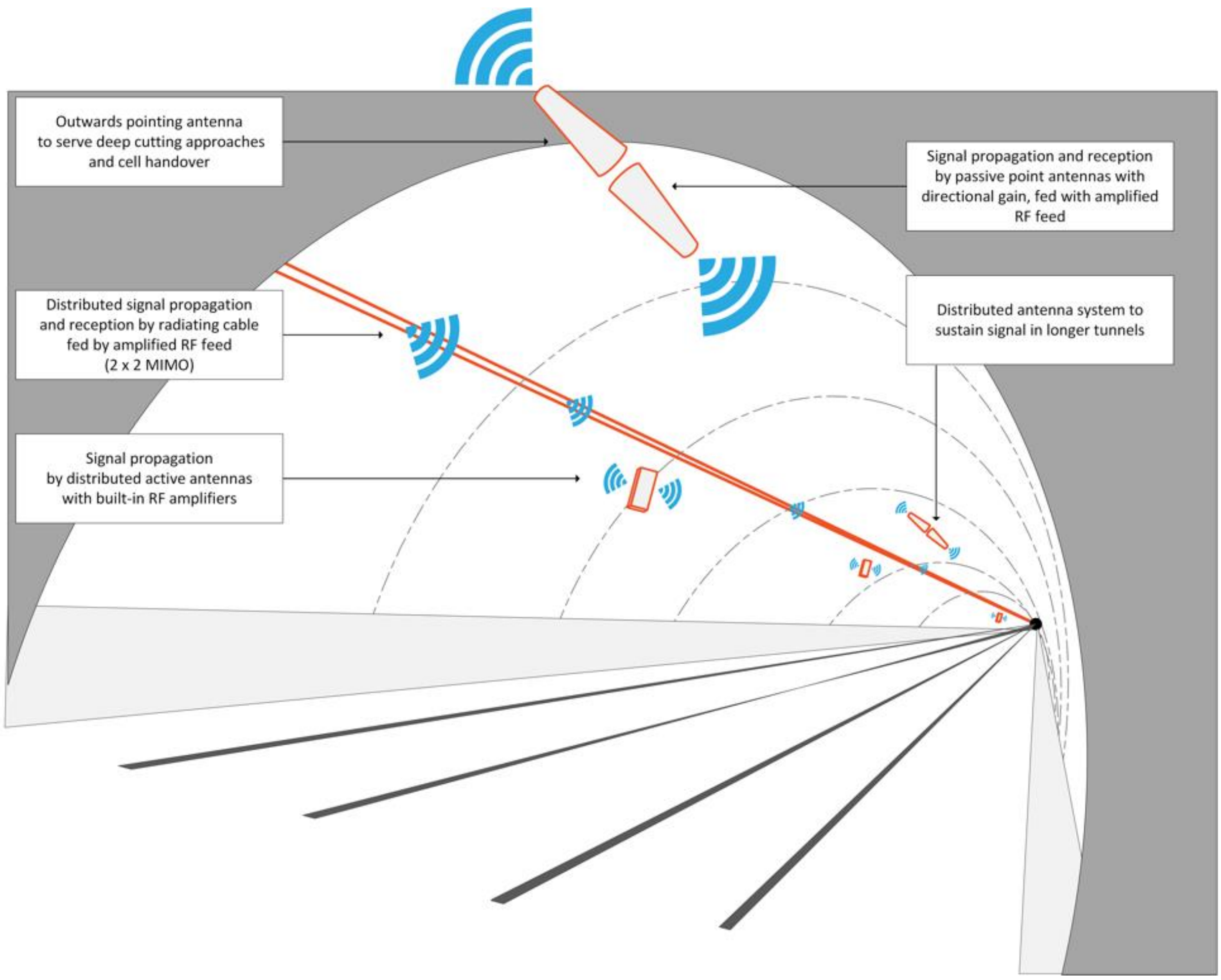


Figure 4 - Tunnel infrastructure wireless connectivity options

Figure 10 offers an overview of how wireless connectivity may be provided to a railway tunnel. Large cellular frequency directional antennas may be installed at the tunnel portal paired with an outward pointing antenna to aid cell handover and fill-in of tunnel approaches within deep cuttings. Antenna elements are usually protected from rain, snow, and icing by insulating radome covers.

Additional antenna elements may be required within longer tunnels to maintain coverage to form a Distributed Antenna System (DAS). Alternatively, distributed radiating cables may be laid offset from the tunnel walls. A pair of radiating cables may be used to achieve a 2 x 2 MIMO configuration (as described in Section 4.3.2). At cellular frequencies up to 3,600 MHz, amplified RF at power levels up to 20W is piped by cable from control equipment to point or radiating cable antenna systems. The same antennas and cables route the received signal from passenger devices.

At higher frequencies such as mmWave, antennas and control equipment are smaller so can be packaged together as active antenna units fed by power cables and optical fibre carrying the RF signal. Signal propagation range at mmWave frequencies is low, so in tunnel installation of such units will likely be required.

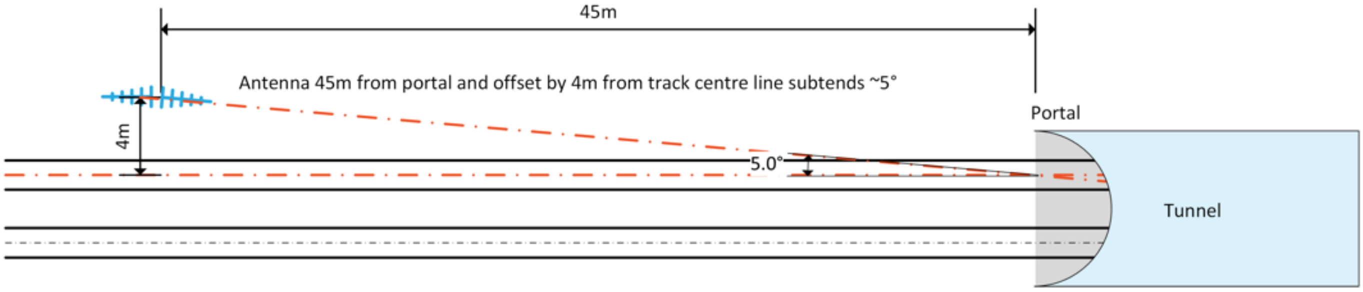


Figure 51 - Typical location of 'Near Portal' antenna

Antennas installed some distance away from the tunnel portal and to the side of the track are appealing to railway infrastructure managers as they are easier to access for installation and maintenance and out of the way of high voltage overhead catenary or sensitive signalling systems and railway operations.

Figure 11 shows that the antenna subtends an angle 5° with respect to the track if sited 45 metres from the tunnel portal and offset 4 metres from the track centre line. The tunnel portal will be in the 'far field radiation' zone and may also receive any reflections and diffraction from the side of cuttings and other structures including at the entrance to the tunnel portal itself, based on principles already discussed in Section 5.

7.2 'Blueprint' architecture elements for tunnel signal propagation infrastructure

Infrastructure approaches for directly radiating antenna solutions include 'Near Portal' (S1), 'At Portal' (S2) and 'In-tunnel' (S3) options, as shown in Figures 12a) through c). Two variants of 'At Portal' (S2.1, S2.2) and 'In-tunnel' (S3.1, S3.2) solutions are also included to compare the use of directional antennas (Figure 12a) versus distributed radiating cable (Figure 12c) approaches at cellular frequencies 700 MHz to 3,600 MHz.

Active antenna systems are preferred at higher frequencies 5 to 60 GHz (Figure 12b). As noted, these integrate the antenna and control/amplifier into a single package but can be treated as just a directional antenna for propagation modelling purposes. Individual unit costs are lower because of the reduced component costs, with commensurate lower power consumption needs. However, this is offset by their typically shorter propagation ranges and hence the need for proportionately more units to deliver the equivalent coverage.

All configurations include a reverse facing directional antenna to support cell-handover coverage or fill-in coverage of tunnel approaches within deep cuttings (Section 6.5):

- **Solution S1: Near Portal** mounts antennas on small trackside masts typically within 30-60m of a tunnel portal and at a slight angle, typically 5°-10° with respect to the tunnel centre line at a height of 4-6m. Masts can be sited for ease of access and installation but suffer higher signal propagation losses between the antenna and tunnel portal.

- **Solution S2: At Portal** mounts antennas 1-2 metres into the entrance and exit of the tunnel portals, either to the side or top, and beam signal directly into the tunnel. This is the preferred solution access, space, and adjacent systems allow as it maximises the usable propagation range of the antenna. The S2.2 variant assumes the use of a linear distributed radiating cable antenna within the tunnel.

- **Solution S3: In-tunnel** are needed for longer tunnels or at higher frequencies as the usable signal propagation range is shorter. Such solutions require space for equipment power and optical fibre cables within the tunnels and often must settle for sub-optimal locations. Both installation and maintenance require disruptive and expensive engineering access to the operational railway. The S3.2 variant assumes the use of distributed radiating cable.

Sections 7.2 and 7.3 contrast directional antenna and distributed radiating cable as technical solutions for tunnel signal propagation and the factors that determine their usable signal propagation range. Whilst Section 8 compares the practical deployment of these different solutions for fitment of a specific tunnel and Section 9 compares costs and the how potential options compare considering the balance of cost, propagation range and practical deployment.

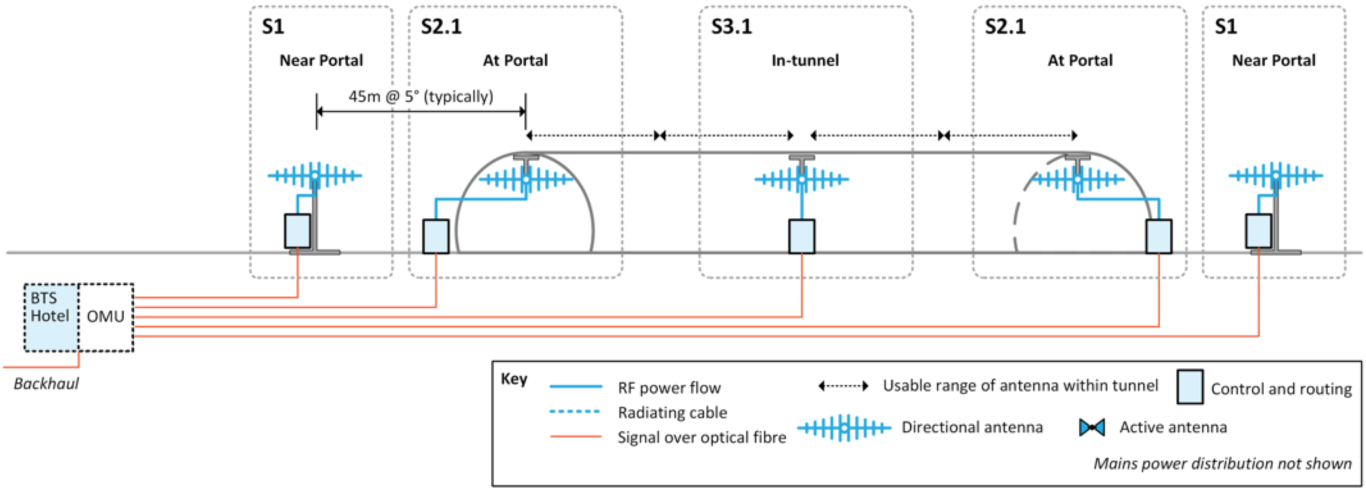


Figure 12a) - Directional Antenna fitment options (Cellular frequencies up to 3,600 MHz)

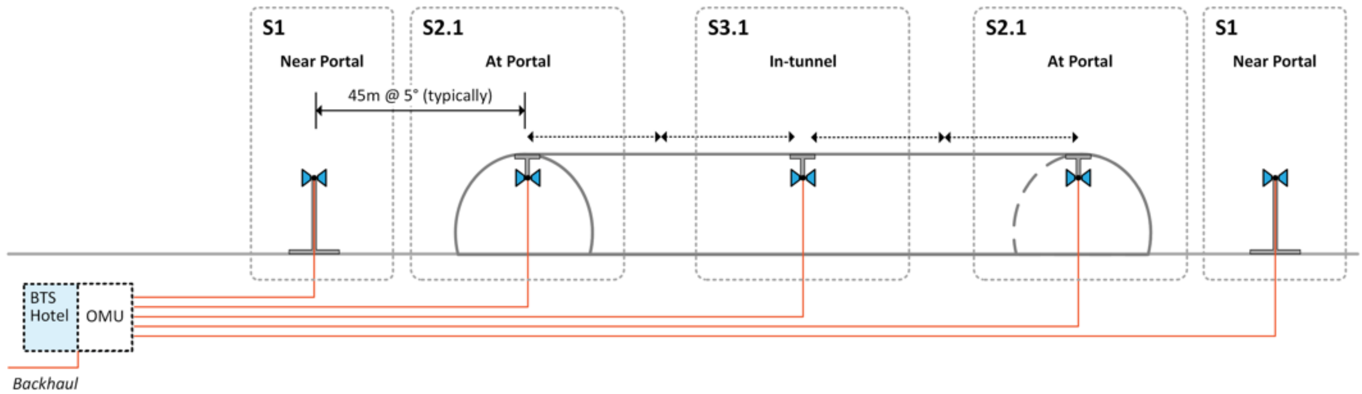


Figure 12b) - Active Antenna fitment options (5-60 GHz)

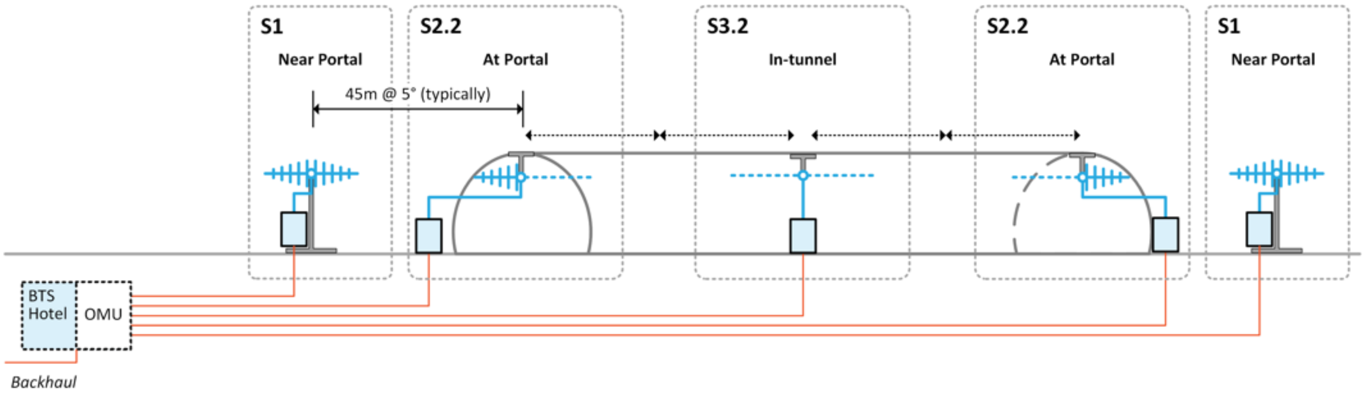


Figure 12c) - Radiating cable fitment options (cellular frequencies up to 3.6 GHz)

7.2 Directional antennas

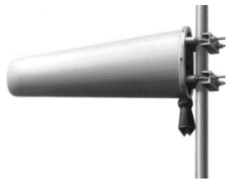
7.2.1 Technology

Directional antennas can be used for all technologies and the entire spectrum range addressed in this study. For cellular technologies (up to 3.8GHz), these antennas are usually "passive", meaning they are installed stand-alone and are not combined with the (active) radio unit.

The two antennas used for RF power link analysis in this study are the 'Ericsson ii Log Per Antenna 742192V02' (Figure 13a) for the 700-2,600 MHz range and the 'Alpha Wireless Panel Antenna AW 3832' (Figure 13b) for 3,400 – 3,800 MHz.

Both antennas can be configured for 2x2 MIMO operation to reduce fading and improve spectral efficiency (Section 4.3.2). The Alpha Wireless panel already comprises multiple antennas.

A cross-polarised array may be formed from a pair of Ericsson antennas, with one rotated on its axis with respect to the other by 90°, noting that the use of cross-polarised antennas within longer tunnels may be adversely affected by polarisation changes imposed by the tunnel surfaces (Appendix 3.7).



a) 700-2,600 MHz Ericsson Log Periodic Antenna (*source: [44-45 z am]*)

b) Directional Antenna: 3.4-3.8 GHz Alpha Wireless Panel Antenna (*source: [44-45 z am]*)

Figure 13 – Directional antenna examples

Similar antenna design principles may be applied to higher frequencies. The shorter wavelength allows smaller antennas with lower peak power output that can be integrated economically as single 'active' antenna packages containing both antenna and control electronics [46, 47]. Directional antennas are also used for external train antennas [48, 49].

Directional antennas are suited to MNO cellular applications for direct connectivity to customer devices. Although the signal is directional, such antennas offers a broad spread, that is extended further by reflection, diffraction or as propagation modes within a waveguide (Section 5).

Signals, albeit strongly attenuated by train losses (Section 6.2), can reach deep into cuttings and tunnels, and through carriages walls and windows to the built-in antennas of passengers' mobile devices.

7.2.2 Signal propagation range constrained by Maximum Allowed Path Loss

The range of a directional antenna system is constrained by the Maximum Allowed Path Loss (MAPL) that can be tolerated within the data link design to achieve the required minimum data transfer rate.

Typical RF power link signal budgets are illustrated in Figure 14 at each of the carrier frequency bands considered by this study. See the box in Section 4.3.3 on the use of dB and dBm units and Table 41 for assumptions about relative quality of service signal power metrics.

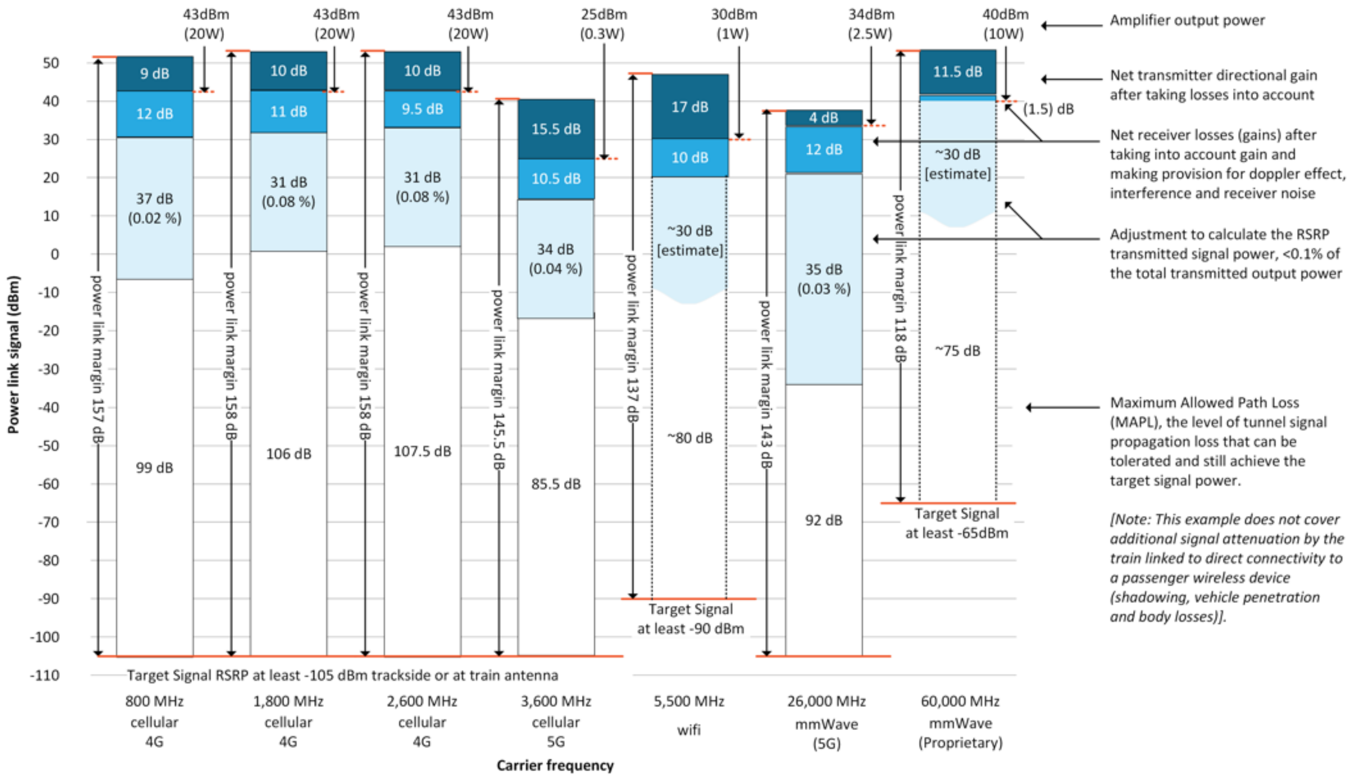


Figure 14 - Typical RF power link margins by carrier frequency: directional antennas

The overall power link margin is as high as 157 dB and represents the ratio of the highest output power to the minimum signal power to be provided to the receiving antenna or passenger device. The power link budget comprises:

- **RF transmitter amplifier peak output power**. This is capped at +43 dBm (20 W) at lower frequencies and may be lower at other frequencies (for example, +25 dBm or 0.3W at 5,500 MHz).
- **Net gain of transmitter antenna system.** The peak directional gain of the transmit antenna intensifies the signal power output even after losses in the cable and passive elements between amplifier and antenna.
- **Net loss of receiver antenna and pre-amplifier.** The directional gain of the receive antenna is lower than the transmitter and (except for 60 GHz mmWave) on partly compensates for other losses accounting for the doppler effect, interference and receiver pre-amplifier added noise.
- **Adjustment for RSRP**. To reduce the RF transmitter total power to the RSRP signal element detected at the receiver. The RSRP metric used to characterise 4G/ 5G services only measures the fraction of total signal power carrying encoded control and data information and is typically less than 0.1% (approximately -30 dB) of the total power transmitted.
- **Maximum Allowed Path Loss (MAPL)**. This sets the maximum usable range of the tunnel propagation system as it sets the maximum level of tunnel signal propagation loss that can be tolerated and still achieve the target signal power to meet minimum data transfer capacity requirements. The range is much less for direct connectivity to passenger wireless devices because MAPL also must cover train-related connectivity losses

(train shadowing, vehicle penetration and body losses).

While the values may vary, the same principles apply to directional antenna systems at cellular, wifi and mmWave frequencies, whether compliant with international standards or proprietary designs. MAPL determines the minimum data rate at the maximum range of the system. In any practical implementation, the tunnel signal levels only sink to the minimum specified levels at the edge of coverage and will be higher elsewhere (in the absence of strong fading effects), as illustratively shown in Figure 6.

Table 13 illustrates the assumptions this study has made about the reduction of MAPL for direct connectivity, caused by train shadowing, vehicle penetration and body losses. Section 6.2 and Table 11 show that such losses may be far higher for many passengers [6].

Table 13 also assumes that direct connectivity is not possible for proprietary trackside wifi or mmWave solutions, reliant on an on-train gateway to redistribute signals, since passenger mobile device are unable to 'decode' such signals.

Variation of Maximum Allowed Path Loss by carrier and application	**800 MHz**	**1,800 MHz**	**2,600 MHz**	**3,600 MHz**	**5,500 MHz**	**26,000 MHz**	**60,000 MHz**
Link Technology	Cellular 4G/5G	Cellular 4G/ 5G	Cellular 4G/ 5G	Cellular 4G/5G	Wifi 4G/ 5G	mmWave 5G	mmWave Proprietary
Overall MAPL (dB)	**99**	**106**	**107.5**	**85.5**	**~80**	**92**	**~75**
Within tunnel at external train Antenna.							
Train Shadowing loss adjustment (location of antenna on end carriages) (dB)	-3	-3	-3	-3	-3	-3	-3
Adjusted MAPL	**96**	**103**	**104.5**	**82.5**	**~77**	**89**	**~72**
Direct Connectivity to passenger device on train					NA	NA	NA
Train Shadowing (single train) (dB)	-				NA	NA	NA
Vehicle Penetration Loss (dB)	-10	-10	-10	-10	NA	NA	NA
User Body Loss (dB)	-10	-10	-10	-10	NA	NA	NA
Crowding Body Loss (dB)	-	-	-	-	NA	NA	NA
Total Train Losses (dB)	**-20**	**-20**	**-20**	**-20**	**NA**	**NA**	**NA**
Adjusted MAPL	**76**	**83**	**84.5**	**62.5**	**NA**	**NA**	**NA**

Table 13 - Impact of additional train losses on Maximum Allowed Path Loss (MAPL) (see Section 6.2)

The impact of train losses is to reduce the range of each tunnel antenna or MNO mast to provide higher signal levels trackside above the -105dBm assumption. This will increase deployment costs as more masts would be required to meet the required signal coverage.

7.3 Radiating cable

7.3.1 Technology

Radiating cables or 'leaky feeders' offer a distributed linear antenna suited for tunnel applications at carrier frequencies up to 2,600 MHz, and 3,600 MHz for short distances (Figure 15 source: [50, 51]).

a) 50-2700 MHz RADIAX RCT7-WBC-4A-RNA with bump, tuned foil, 1-5/8 in (41mm)

b) 30-3,800 MHz EUCARAY RMC 114-G "A" Series radiating cable, 1¼ in (32 mm)

Figure 15 - Coaxial Radiating Cable Types

Leaky feeder cable comprises two coaxial conductors separated by an insulator. Regular slots or other irregularities in the outer conductor leak electromagnetic fields able to couple with nearby antennas, including those built into passenger wireless devices.

Radiating cables are mounted and stood off from the wall or roof of the tunnel or attached to a guide wire. Signal is injected at similar power levels to directional antennas into each radiating cable with a terminating impedance to reduce standing waves.

Some designs adjust the shape of the central conductor to create stop bands to minimise out-of-band electrical noise (Figure 15a). Electromagnetic coupling across the air gap is a complex combination of near field and far field interactions. Cable manufacturers provide empirical predictions of coupling loss at fixed radial distances from the cable (typically 2 and 5 metres). Coupling loss increases with distance from the cable and with carrier frequency. The signal propagating along the cable also decays exponentially along its length. The equivalent to the MAPL for a directional antenna is the combination of fixed air gap loss plus the variable loss along the cable.

Radiating cable offers the most stable signal levels for direct connectivity to passengers' devices throughout a train. There are no direct train shadowing losses as the cable runs alongside the full length of the train often at window height. Other passing trains will affect the coupling loss of the airgap. Direct distances between each passenger device and the radiating cable are short (between 1 and 8 metres), reducing both vehicle penetration and body losses within the passenger saloon.

Radiating cable would also work well as an indirect signal relay to an external train antenna and train-based gateway. A 2 x 2 MIMO configuration can also be established by laying a pair of separately fed cables alongside each other.

Set against the obvious benefits of such cable, it is also the most expensive of the various tunnel wireless distribution technologies. It also requires additional fixing materials, clearance outside of the train's kinetic envelope, and access to the operational railway for both installation and maintenance.

7.3.2 Alternative Tunnel Fitment Configurations

The option selection tool used in Section 9 assumes a standard base case configuration for radiating cable fed from a single cable amplifier. This section shows how the base case supports usable range calculations for both dual track and single bore tunnels and how power splitters or additional cables can be used to rebalance signal levels in dual track tunnels.

The base case configuration is shown in Figure 16. It assumes a dual track tunnel with a pair of radiating cables mounted to one side wall, able to support 2 x 2 MIMO.

The cables are nominally 2 metres from the centre of a railway carriage passenger saloon on the nearer track and 5 metres from a carriage on the far track. For the reference design of radiating cable used (Table 43), the air gap coupling loss at 2 metres increases from 75 to 82dB as the carrier frequency increases from 800 to 3,600 MHz, and the coupling loss at 5 metres is 8 dB worse than at 2 metres.

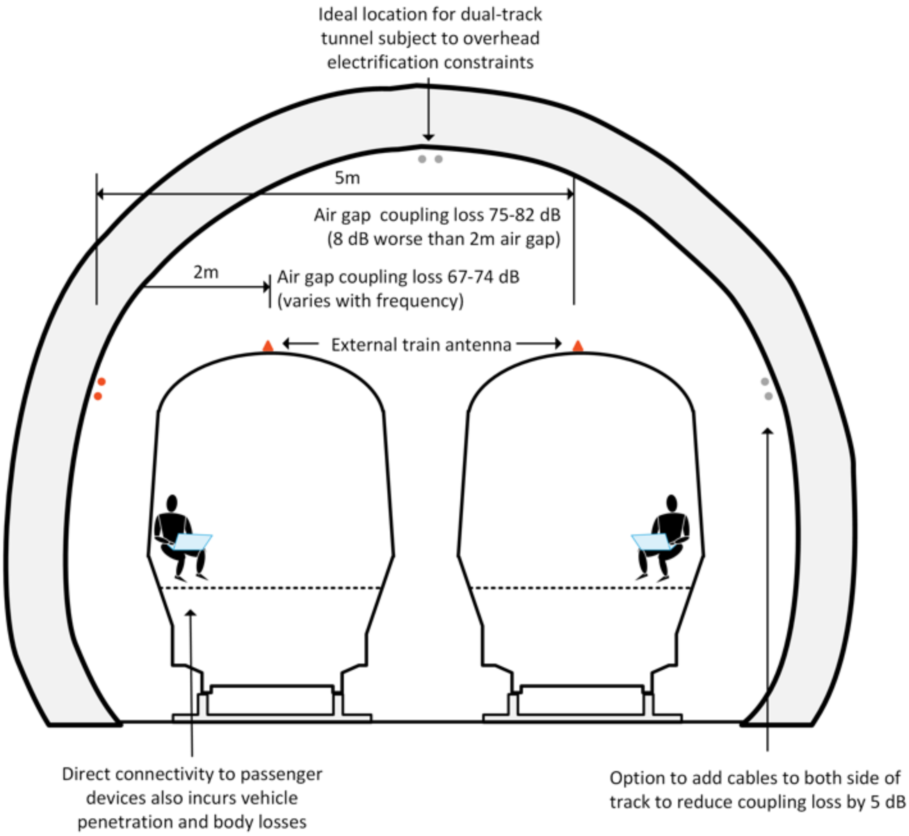


Figure 16 - Tunnel fitment configuration options: radiating cable

The following options were considered and summarised in Table 14:

- **Option 1: Dual track tunnel with radiating cable equidistant from each track**. This option locates the cable in the tunnel roof area (between 11 and 1 o'clock) and may not be feasible because of overhead electrification requirements or electromagnetic compatibility. This balances tunnel signal provided to each track, increasing coupling loss on the near track by approximately 4 dB while reducing loss on the far track by 4 dB.

- **Option 2: Dual track tunnel with radiating cables fitted to both sides of the tunnel**. This option offers the same signal level to both carriages but reduces the average signal power at 2 metres from the cable by 3 dB as only half the power flows down each cable. It is also more expensive to deploy the second set of cables and power splitter. Compared with the base case, the near train suffers a 3 dB reduction in signal power while the train on the far side gains +5 dB of signal.

- **Option 3: A pair of single bore tunnels with a single radiating cable down the side of each.** This is in essence the same as Option 2 with the two sets of radiating cables split between the tunnels. Each train will experience signal power 3 dB worse than the base case near track example.

Configuration Options	Tracks per Tunnel	Costs	Gains (dB)	Losses (dB)	MAPL relative to base case (dB) near	far
Base case: One set of side cables	2	-	-	-8 (far train)	0	-8
Option 1: Move side cables to top of tunnel [subject to electrification constraints].	2	-	~ +4 (far train)	~ +4 (near train)	-4	-4
Option 2: Add cables far side plus splitter to share amplifier	2	Extra cable	+8 (far train)	-3 (splitter)	-3	-3
Option 3: Two single bores as base case plus splitter to share amplifier	2x1	Extra cable	-	-3 (splitter)		-3

Table 14 - Impact of radiating cable configuration options on MAPL

7.3.3 Signal propagation range constrained by Maximum Allowed Path Loss

Like the directional antenna, the usable signal propagation range of a radiating cable is constrained by the MAPL that can be tolerated within the data link design to achieve the required minimum data transfer rate. Typical RF power link signal budgets are illustrated in Figure 17 at each of the carrier frequency bands between 800 MHz and 3,600 MHz.

See the box in Section 4.3.3 on the use of dB and dBm units and Table 43 for assumptions.

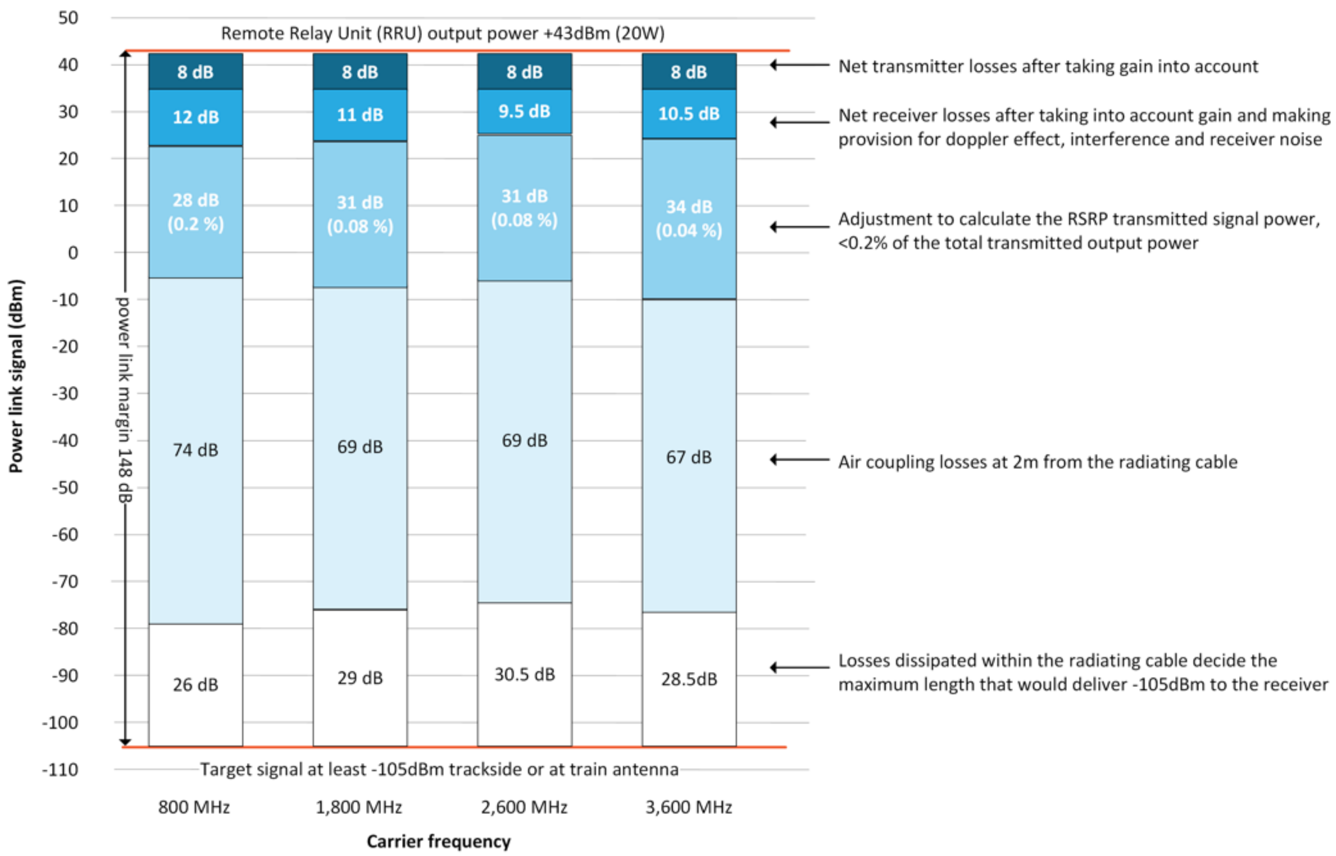


Figure 17 - Typical RF power link margins: radiating cable

Radiating cables are fed by cable from amplifiers like those used for directional antennas with RF output power capped at +43 dBm (20 W), with the requirement to achieve tunnel signal power levels of -105 dBm. This offers an overall power link margin of 148 dB, the ratio of the highest output power from the transmitter amplifier to the minimum signal power within the tunnel (ignoring train losses).

The power link budget (Figure 17) comprises:

- **RF transmitter amplifier peak output power.** This is assumed capped at +43 dBm (20W) for all frequencies.
- **Net loss of transmitter distribution system.** There is no gain just distribution losses between the amplifier and the radiating cable.
- **Net loss of receiver antenna and pre-amplifier**. As with directional antennas, the directional gain only partly compensates for other losses accounting for the doppler effect, interference, and receiver pre-amplifier added noise.
- **Adjustment for RSRP**. This reduces the RF transmitter total power to the RSRP signal element metric as specified for the receiver. The RSRP metric used to characterise 4G/ 5G services only measures the fraction of total signal power carrying encoded control and data information and is typically less than 0.1% (approximately -30 dB) of the total power transmitted.
- **'Air Gap' coupling loss**. This varies with radial distance (1 to8 metres across the tunnel cross-section) and carrier frequency with empirical performance tables supplied by the cable manufacturer. It contributes to MAPL but does not vary with distance into the tunnel.
- **Radiating cable losses**. This is the contribution towards MAPL that varies with distance into the tunnel and determines the usable range of a radiating cable system. This example does not show the further reduction to MAPL caused by train losses for direct connectivity to passenger devices. However, these losses are smaller than for directional antenna solutions.

Radiating cable solutions are more predictable because they depend far less on the propagation characteristics of the tunnel itself.

Table 15 estimates the usable range of radiating cable systems for three cases at each carrier frequency band. The base case is for the target signal to be reached within the tunnel at 2 metres from the cable, serving the near train from Figure 16.

Option 1 is the range at which the same signal would be achieved at 5 metres from the cable, able to serve the far track (i.e. to provide a signal to a train on the other track of a dual-track single bore tunnel). Option 2 looks at direct connectivity to the near train where additional train losses to reach passenger devices is 10 dB. Option 3 repeats Option 2 for the far track.

The range distances are calculated by dividing the cable loss margin by the manufacturers' stated rate of radiating cable loss (dB/km) and multiplying by 1,000 to state the range in metres.

Cable range calculations **to provide -105 dBm target signal level (RSRP)**	**800 MHz**	**1,800 MHz**	**2,600 MHz**	**3,600 MHz**
Radiating cable Loss (dB/km)	19 dB/km	33 dB/km	51 dB/km	79 dB/km
Base Case: External train antenna 2 metres from radiating cable near train)				
Cable Loss Margin (dB)	26 dB	29dB	30.5 dB	28.5 dB
Calculated usable range	**1,400 m**	**900 m**	**600 m**	**350 m**
Option 1: External train antenna 5 metres from radiating cable (far train)				
Cable Loss Margin (dB)	18 dB	21 dB	22.5 dB	20.5 dB

Cable range calculations to provide -105 dBm target signal level (RSRP)	800 MHz	1,800 MHz	2,600 MHz	3,600 MHz
Calculated usable range (metres)	**950 m**	**650 m**	**450 m**	**250 m**
Option 2: Direct connectivity to passenger device 2 metres from radiating cable (near train) with additional 10 dB in vehicle penetration and body losses				
Cable Loss Margin (dB)	16 dB	19 dB	20.5 dB	18.5 dB
Calculated usable range (metres)	**850 m**	**600 m**	**400 m**	**200 m**
Option 3: Direct connectivity to passenger device 5 metres from radiating cable (far train) with additional 10 dB in vehicle penetration and body losses				
Cable Loss Margin (dB)	8 dB	11 dB	12.5 dB	10.5 dB
Calculated usable range (metres)	**420 m**	**330 m**	**250 m**	**130 m**

Table 15 - Usable range estimates – radiating cable (Source: Figure 16)

7.4 Prediction Modelling of signal propagation range

7.4.1 Overview

Tunnel coverage is a unique challenge that is not addressed in normal country-wide mobile network planning.

Like an underground parking lot, the signal from an outdoor macro site does not propagate into a tunnel reliably. Solutions tend to be niche and usually require a specific design for each tunnel, given the potential variances in their type, length, and coverage requirements as noted earlier. Furthermore, the train carriages and passengers themselves impose further limitations. All these factors need to be considered in the RF design process.

A dedicated tunnel solution may also have to be dimensioned for high capacity to offer uninterrupted service to all passengers regardless of their choice of mobile operator, even though the train might spend only a few seconds inside it. Furthermore, there are also cellular handover considerations, where, as the train transitions from outdoor coverage to tunnel coverage and vice versa, it requires the tunnel solution to provide overlapping coverage to allow for the time needed to undertake a seamless handover.

Nonetheless, it should be noted that external macro sites can provide a level of in-tunnel coverage for shorter tunnels if the site is next to the railway track and close to the tunnel with antennas pointing towards the tunnel portal.

7.4.2 Understanding propagation behaviour in tunnels

RF propagation in tunnels is very different to outdoor and other indoor environments. Outdoor and indoor propagation and prediction models are well established, tuned, optimised and proven. This is not the case for tunnel propagation environments where there is limited published data and hardly any commercially available prediction model tools.

Key variables affecting tunnel predictions include:

- Propagation behaviour variations for different frequencies.
- The variation of the tunnel profile (impacting signal propagation).
- The impact of trains in the tunnel (blocking and reduced propagating space between the train and tunnel).
- Tunnel lining material and surface structure (impacting signal reflection and absorption rate).
- Curvature of tunnels (has a different impact for different tunnel lining materials and surfaces).
- Installations and infrastructure in the tunnel (impacting propagation and add more reflected multi-path.

The wave propagation in the tunnel can be generally divided into five distinctive regions:

1) Near shadowing zone.
2) Free space propagation zone.
3) Multi-mode propagation zone.
4) Fundamental propagation zone.
5) Extreme far zone.

The near shadowing zone is the zone in front of the tunnel antenna, where the train body itself blocks the signal, as seen in Figure 18. In this case, the train body may block the first and higher order of the Fresnel zones, ending when the train passes through completely in front of the antenna (that is the length of the zone equals the length of the train).

This configuration assumes two antennas on the train roof, one in front and one in the back. If this is not the case, then depending on the antenna placement on the train roof and the travel direction of the trail it may result in a greater near shadowing zone.

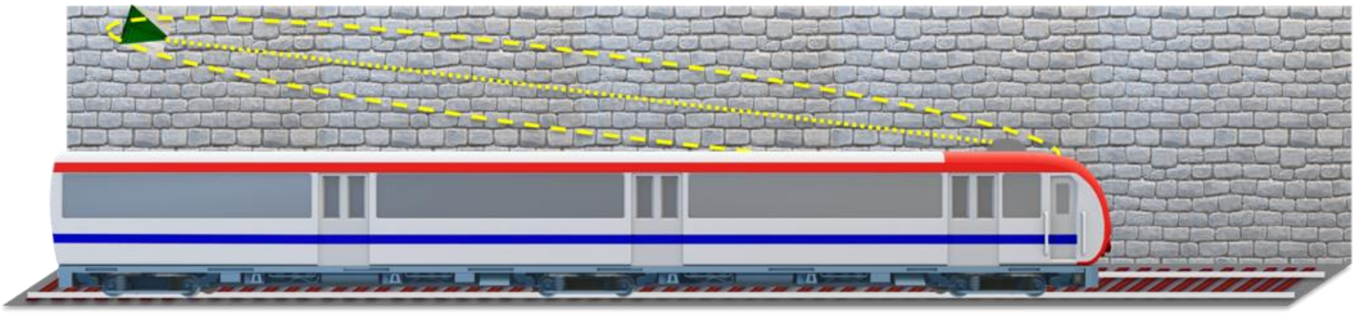


Figure 18 - The train body blocking the signal to the antenna (blockage of 60% or more of the First Fresnel zone)

The free space propagation zone characterises the part of the tunnel where the signal travels without any obstructions, according to the free space principles. However, as the separation distance between the antenna increases, so does the first Fresnel zone. There is a point where 60% of the first Fresnel zone is obstructed by the tunnel walls, which location is defined by the antennas' distance, tunnel cross-section and operating frequency, and at which location, the free space propagation assumptions can no longer be valid (Figure 19). It is possible though, that for large enough trains, the near shadowing zone is longer than the free space one, and as a result, the free space propagation zone does not exist in such scenarios.

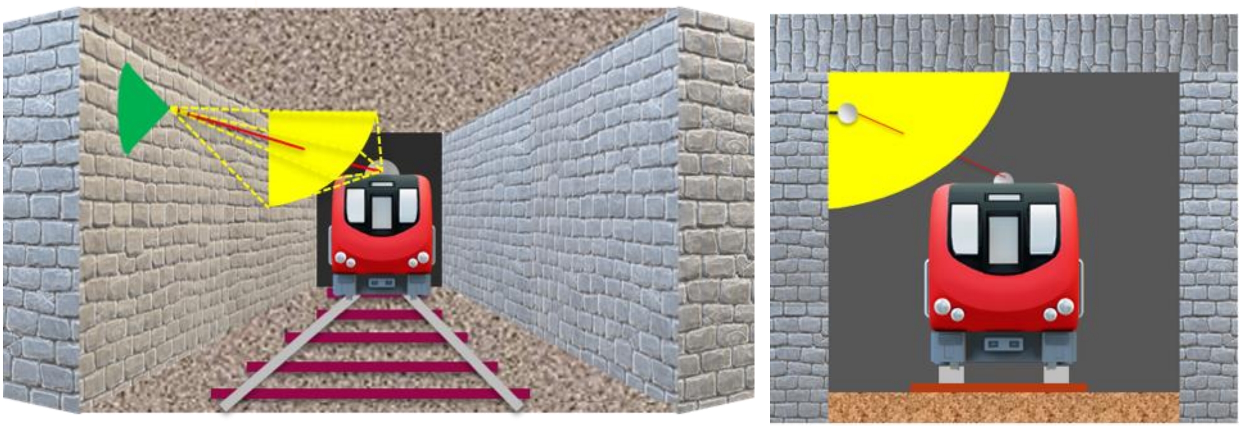


Figure 19 - Blockage of the First Fresnel zone from the roof and the side wall of the tunnel

After the free space propagation zone, the tunnel acts as a waveguide, which gives rise to the propagation of multiple electromagnetic modes. This is the multi-mode propagation zone. The propagation in this zone depends on the tunnel itself and its characteristics, such as the walls' electromagnetic properties, tunnel cross-section, and the operating frequency.

The near shadowing, free space, and multimode propagation zones characterise the near propagation region. When all the higher electromagnetic modes have undergone at least one reflection on the walls of the tunnel, and therefore assumed that they are negligible, only the fundamental electro-magnetic modes continue to propagate, in the zone that is termed as the fundamental propagation zone.

Finally, at a far enough distance into the tunnel, even the fundamental modes have suffered one reflection and therefore the waveguide effect vanishes. From then on, the extreme far zone is considered. It should be noted though that in most cases, the length of the tunnel may not be long enough for this zone to exist (i.e. the tunnel ends before the end of the fundamental propagation zone).

The fundamental propagation and extreme far zones characterise the far propagation regions.

7.4.3 Calibration\ validation\ adaptation of the prediction model

There are three sources of information, which are used in the calibration phase:

1) Measurements in tunnels as part of this project.
2) Third party measurements in tunnels that were provided to the study team.
3) GSM-R yellow train data.

The propagation model has several input parameters. Some of these parameters are known (such as the location of the transmitter and receiver antennas and the dimensions of the tunnel cross-section), while others had to be estimated (such as the electromagnetic properties of the lining material, the roughness of the tunnel walls, and the walls' tilt). It should be noted that the model assumes a rectangular tunnel shape, and therefore, the 'modified' width and height of the tunnel was calculated, which adds to the model's inaccuracies.

Based on the measurement data and their comparison with the theoretical expectations, it was necessary to proceed to an adaptation stage, to align the propagation model with the measurements:

- Measurement data didn't include the presence of a train inside the tunnel and therefore the existence and length of the near shadowing zone could not be verified, and hence this zone was excluded from the model.
- The theory suggests that at long distances, at the extreme far zone, the signal propagates as in free space, however, this was not supported by the measurements and therefore it was excluded.
- The prediction of the multimode propagation, which is responsible for the rapid fluctuations in the pathloss, is sensitive to the environmental parameters (such as tunnel cross-section dimensions, and transmitter and receiver locations), exact figures of those were not always available (average figures for the tunnel cross-section dimensions were used rather than specific ones for each tunnel) and therefore it was not possible to accurately predict its behaviour and hence it was excluded from the model.
- Other unknown parameters that would affect the signal propagation in tunnels were internal tunnel infrastructure and variety of lining material.
- Most of the tunnels measured did not have a sufficient length to fully identify the tunnel propagation characteristics.
- A combination of a free-space loss and fundamental mode propagation regions provided a very good match.

To estimate the unknown parameters, a heuristic algorithm was created, which searched for the near optimal set of parameters that minimised the error between measurements and predictions. This algorithm tried thousands of different combinations of the parameters to find the set that matches 'best' the data.

Whilst the algorithm did not perform an exhaustive search of all the possible combinations (as this was an impossible task), a sufficient subset was found providing a near-optimal solution. To have a more logical set of parameters, the measurements from all frequency bands for each scenario were used to find a common set of parameters for that tunnel.

The measurement results showed that the signal can travel quite far in an empty tunnel, and in most cases farther than the actual length of the tunnel. In such cases, the model was used to predict the signal propagation in the tunnel for longer distances.

For the prediction of the tunnel propagation from an external antenna, the model assumed a free-space loss propagation to the tunnel portal, a portal loss ($\mathbf{L_{mouth}}$) entering the tunnel and then fundamental mode propagation. The portal loss is calculated as $\mathbf{L_{mouth} = a \log_{10}(f)}$, where **a** is the portal loss factor and **f** is the frequency in MHz. In this step, it was assumed that all the parameters are the same as in the portal antenna scenario and therefore, only the constant a needed to be estimated.

7.5 RF testing of signal propagation range

Acknowledgements:
The test measurements described in this section and Appendix 4 were made with the permission and active co-operation of the owners and operators (and their contractors) of the following tunnels:

- ***Dudley** Tunnel is operated and maintained by Black Country Innovative Manufacturing Organisation (BCIMO) who provided free access.*
- ***Standedge Old** Tunnel is owned, operated and maintained by Network Rail. The tests were supervised by the NR Route Telecoms Minor Works Eastern Region Team.*
- ***Copenhagen** Tunnel. The Eastern bore is currently non-operational, being used as an access tunnel. The other two bores remain fully operational on the East Coast Main Line. The tunnel is owned, operated and maintained by Network Rail. Essential support during the test was provided by Alan Dick Communications.*

RF signal propagation loss measurements have been undertaken using directional antennas to confirm the principles described in Section 5, the prediction modelling described in Section 7.4 and measurements directly relevant to brick-lined tunnels that account for almost 70% of GB rail tunnels.

See Appendix 4 for photographs and more details of the approach, the tunnels tested, the test and equipment setup, measured tunnel RF signal propagation loss characteristics, and practical lessons learned.

7.5.1 Tunnel RF signal propagation loss measurements

A major aim of this study has been to understand the signal propagation loss characteristics of GB railway tunnels, primarily through desktop modelling but validated with field testing at a small number of sites.

Direct testing of tunnel signal propagation loss requires intrusive access over a period of up to five days per tunnel. Tunnel sites needed to be representative of the GB tunnel population and long enough to establish the true usable range. However, they also needed to be non-operational at the time of testing, made available and supervised by the tunnel infrastructure manager within the timescales of the study, and physically accessible.

Three tunnels were tested at Dudley in the West Midlands, Standedge Old Tunnel in the Pennines, and Copenhagen Tunnel on the approach to King’s Cross, London:

- **Dudley Tunnel** (BCIMO) is a dual-track brick-lined bored tunnel 844 metres long with only one of the tracks installed. The tunnel is mainly straight for measurements starting from the south portal but has a curvature of radius 805m for measurements from its north portal.

- **Standedge Old Tunnel** (NR) is a 4,880 metres long straight single-track brick-lined bored tunnel. It is one of a system of parallel tunnels sharing cross passages and ventilation shafts. The other tunnels carry canals and two fully operational rail tunnels. The tunnel has long been out of operation and lacks power, and lighting, and was only accessible by foot or road vehicle. The track has been removed and the remaining track bed has many potholes, often water filled. On one test day the study team had to share access with a team carrying out maintenance of the canal tunnel.

- **Copenhagen Tunnel Eastern bore** (NR) is a straight dual-track brick-lined tunnel 543 metres long and was used over a single test day to provide additional confidence in the results gathered at Dudley and Standedge and compare the sensitivity to transmitter and receiver position across the tunnel cross-Section. It is non-operational and currently used as an access road.

RF signal propagation loss measurements were made in empty tunnels at spot carrier wave frequencies (as described in Appendix 4.3). Each test run measured one frequency at a time by towing or pushing the receiver away from the transmitter deep into the tunnel. This means some variation in receiver location and alignment from run to run that may affect the results.

Signal transmitter positions were chosen to emulate 'Near Portal' (Solution S1) and 'At Portal' (Solution 2.2) architectures (Section 7.1 and Figures 12a and 12b). Receiver locations were chosen to represent tunnel locations through which trains would pass, both for direct connectivity to passenger wireless devices and an external train antenna mounted on the roof of the train. This provided at least two locations to compare the sensitivity of signal propagation loss to receiver position. However, it could not emulate the presence of a real train or assess any of the additional train loss mechanisms described in Sections 6.2 and 6.3.

No attempt was made to measure the signal propagation loss of radiating cable.

7.6 Antenna range lookup tables

This section applies the modelling and test work plus other team assumptions from experience and international literature to compile lookup tables listing the expected usable range of different blueprint architecture elements. The lookup tables take the following dependencies into account:

- Purpose of tunnel data link, whether direct connectivity to passengers' devices onboard a train or a signal relay link to an external train antenna (as described in Section 4.1).
- Blueprint propagation architecture element types for 'Near Portal', 'At Portal' or 'In-tunnel' applications of directional antennas or radiating cable solutions (see Section 7.2).
- Six tunnel construction material types and size, assuming most tunnels are straight (Section 3.2).
- Seven carrier frequencies serving different wireless technologies and applications (see Section 4.3).

7.6.1 Directional Antenna - Solution S1 Near Portal

Table 16 shows the expected usable range from a near-portal antenna (45m from portal at an angle of 5°) to an external train antenna as part of an indirect on-train gateway solution.

Range to external train antenna (all in metres)	**800 MHz**	**1,800 MHz**	**2,600 MHz**	**3,600 MHz**	**5,500 MHz**	**26,000 MHz**	**60,000 MHz**
Link technology	Cellular 4G/5G	Cellular 4G/ 5G	Cellular 4G/ 5G	Cellular 4G/5G	Wifi 4G/ 5G	mmWave 5G	mmWave Proprietary
Rock – Single Track	900	1,400	2,900	2,000	150	400	300
Rock – Dual Track	1400	2,500	3,000	>5,000	150	400	300
Brick – Single Track	2000	2,750	2,000	3,250	150	400	300
Brick – Dual Track	1400	2,250	2,750	3,500	150	400	300
Concrete – Single Track	2250	3,000	2,500	4,250	150	400	300
Concrete – Dual Track	2250	3,000	2,500	4,250	150	400	300

Table 16 - Usable signal range to external train antenna: S1 Near Portal directional antenna

Table 17 shows the expected usable range from a near-portal antenna (45 metres from portal at an angle of 5°) for direct connectivity to a passenger wireless device on a train.

Range by direct connectivity to passenger wireless device (metres)	800 MHz	1,800 MHz	2,600 MHz	3,600 MHz	5,500 MHz	26,000 MHz	60,000 MHz
Link technology	Cellular 4G/5G	Cellular 4G/ 5G	Cellular 4G/ 5G	Cellular 4G/5G	Wifi 4G/ 5G	mmWave 5G	mmWave Proprietary
Rock – Single Track	25	25	25	25	NA	NA	NA
Rock – Dual Track	25	25	25	25	NA	NA	NA
Brick – Single Track	100	25	25	25	NA	NA	NA
Brick – Dual Track	200	100	125	150	NA	NA	NA
Concrete – Single Track	50	50	25	25	NA	NA	NA
Concrete – Dual Track	25	25	25	25	NA	NA	NA

Table 17 - Usable signal range, direct connectivity to passenger devices: S1 Near Portal directional antenna

7.6.2 Directional Antennas - Solutions S2.1 Portal and S3.1 In-Tunnel

Table 18 shows the expected usable range from an ‘At Portal’ (S2.1) or ‘In-tunnel’ (S3.1) directional antenna to an external train antenna as part of an indirect on-train gateway solution.

Range to external train antenna (metres)	800 MHz	1,800 MHz	2,600 MHz	3,600 MHz	5,500 MHz	26,000 MHz	60,000 MHz
Link technology	Cellular 4G/5G	Cellular 4G/ 5G	Cellular 4G/ 5G	Cellular 4G/5G	Wifi 4G/ 5G	mmWave 5G	mmWave Proprietary
Rock – Single Track	600	2,100	2,100	2,750	450	750	450
Rock – Dual Track	2,400	2,000	2,750	>5,000	450	750	450
Brick – Single Track	4,250	>5,000	>5,000	3,750	450	750	450
Brick – Dual Track	1,750	3,000	4,000	4,000	450	750	450
Concrete – Single Track	3,000	5,000	4,250	>5,000	450	750	450
Concrete – Dual Track	2,500	>5,000	4,000	>5,000	450	750	450

Table 18 - Usable signal range to external train antenna: S2.1 portal or S3.1 in-tunnel directional antenna

Table 19 shows the expected usable range from an ‘At Portal’ (S2.1) or ‘In-tunnel’ (S3.1) directional antenna for direct connectivity to a passenger wireless device on a train. This applies the additional train loss assumptions stated in Table 11.

Range by direct connectivity to passenger wireless device (metres)	800 MHz	1,800 MHz	2,600 MHz	3,600 MHz	5,500 MHz	26,000 MHz	60,000 MHz
Link technology	Cellular 4G/5G	Cellular 4G/ 5G	Cellular 4G/ 5G	Cellular 4G/5G	Wifi 4G/ 5G	mmWave 5G	mmWave Proprietary
Rock – Single Track	25	50	25	100	NA	NA	NA
Rock – Dual Track	125	25	25	25	NA	NA	NA
Brick – Single Track	1,100	150	100	300	NA	NA	NA
Brick – Dual Track	700	550	250	800	NA	NA	NA
Concrete – Single Track	25	50	25	100	NA	NA	NA
Concrete – Dual Track	300	125	150	50	NA	NA	NA

Table 19 - Usable signal range, direct connectivity to passenger devices: S2.1 portal or S3.1 in-tunnel directional antenna

7.6.3 Distributed linear radiating cable Antenna - Solutions S2.2 Portal and S3.2 In-Tunnel

Table 20 shows the expected usable range in metres from an ‘At Portal’ (S2.2) or ‘In-tunnel’ (S3.2) radiating cable to an external train antenna as part of an indirect on-train gateway solution.

Receiver location	Tunnel size	800 MHz	1,800 MHz	2,600 MHz	3,600 MHz
External train antenna	Single track (dual bore)	1,700 m	1,000 m	650 m	400 m
Passenger device	Single track (dual bore)	900 m	450 m	300 m	150 m
External train antenna	Dual track	1,800 m	1,100 m	750 m	450 m
Passenger device	Dual track	1,100 m	500 m	350 m	200 m

Table 20 - Usable signal range to external train antenna: S2.2 portal or S3.2 in-tunnel radiating cable

7.7 Findings

Table 21 summarises the conclusions from the usable signal propagation range lookup tables. Direct connectivity solutions using directional antennas are not possible for single track tunnels (except 800 MHz brick tunnels) or above 5 GHz. Radiating cable solutions are feasible in all single and dual track tunnels up to 2.6 GHz but will not work at all above 4 GHz.

‘Blueprint’ architecture and Antenna Type	**Cellular (<3.8 GHz)** Indirect to External Train Antenna*	**Cellular (<3.8 GHz)** Direct Connectivity Single track	**Cellular (<3.8 GHz)** Direct Connectivity Dual track	**mmWave (5-60 GHz)** Indirect to External Train Antenna *	**mmWave (5-60 GHz)** Direct Connectivity
S1 Near portal directional antennas	Yes	No	Yes	Yes	No
S2.1 At Portal directional antennas	Yes	No except 800MHz Brick	Yes	Yes	No
S2.2 At Portal radiating cables	Yes	Yes	Yes	No	No
S3.1 In-tunnel directional antennas	Yes	No	Yes	Yes	No
S3.2 In-tunnel radiating cable	Yes	Yes	Yes	No	No

* Requires trains fitted with external antenna and on-board gateways to service passenger devices

Table 21 - Suitability of blueprint architectures and carrier frequencies for direct connectivity

8 Tunnel fitment designs and practical deployment considerations

This section describes how the 'blueprint' architecture signal propagation elements introduced in Section 7 may be configured to fitment a specific tunnel with wireless connectivity.

It compares the various options and practical deployment considerations, first for passive directional antennas and radiating cables at cellular frequencies 700 MHz to 3,600 MHz, and then for active antennas operating at higher frequencies, 5 to 60 GHz, for wifi and mmWave applications.

The impact on fitment costs and how fitment costs, usable signal propagation range and practical deployment considerations may be used for a high-level comparison of the different options is discussed in Section 9.

8.1 Tunnel wireless fitment design at cellular frequencies

Given the restriction on space within the railway environment, MNOs operating at cellular frequencies (700 MHz to 3,600 MHz) have agreed to the share common components as defined by the 'Joint Operators Technical Specification – Rail' (JOTS Rail) [8].

This includes directional antennas, radiating cables, DAS and associated signal distribution components. MNOs supply their own Remote Radio Units (RRUs) that connect directly to the passive directional antennas or radiating cables to transmit and receive RF signal and connect back over optical fibre cable to Base Band Unit (BB) nodes within their own networks at Base Transceiver Stations (BTS).

A different DAS approach is needed for longer tunnels that need additional in-tunnel antennas to achieve full signal coverage and cell-handover, as optical fibre links are needed between each 'active' antenna and the MNO equipment. The standard approach for longer tunnels is to co-locate MNO network node equipment within a common equipment room or 'BTS hotel' alongside a shared Optical Master Unit (OMU). The OMU acts as the interface linking the multiple tunnel antenna optical fibre feeds with each MNO BBU.

8.1.1 Configuration Options

Figures 20a) to 20e) show how the blueprint architecture elements (S1, S2.1, S2.2, S3.1 and S3.2) introduced in Section 7 and Figures 12a) though 12c) may be configured to fit a specific railway tunnel at cellular frequencies.

The base scope is assumed to include active and passive RF equipment, sited on local railway infrastructure, and able to use local mains power supplies, and earthing and bonding points supplied by others. The scope includes power and optical fibre cables needed within the tunnel (which is a variable cost dependent on tunnel length). Longer tunnels requiring 'In Tunnel' (S3) elements also include provision for an Optical Master Unit (OMU) at a BTS hotel and laying optical fibre connections of up to 1km through existing cable routes, ducts or troughs.

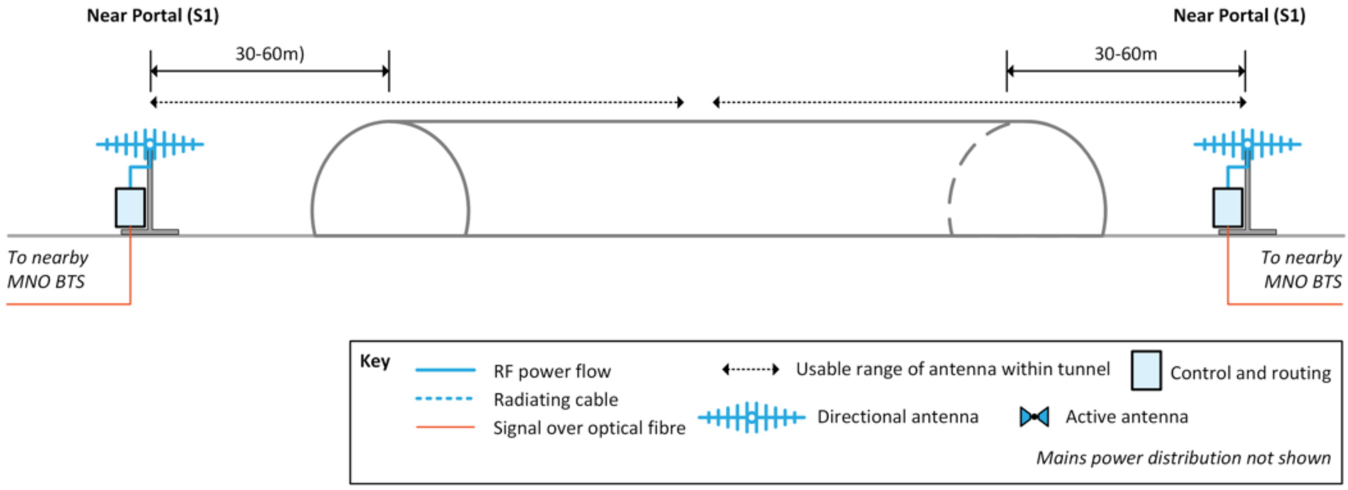


Figure 20a) - Tunnel fitment configuration options: S1 Near Portal (700-3,600 MHz)

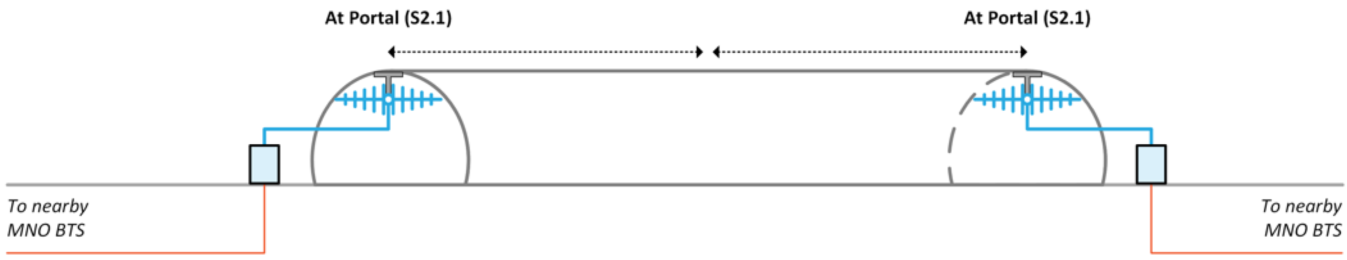


Figure 20b) - Tunnel fitment configuration options: S2.1 At Portal directional antennas (700-3,600 MHz)

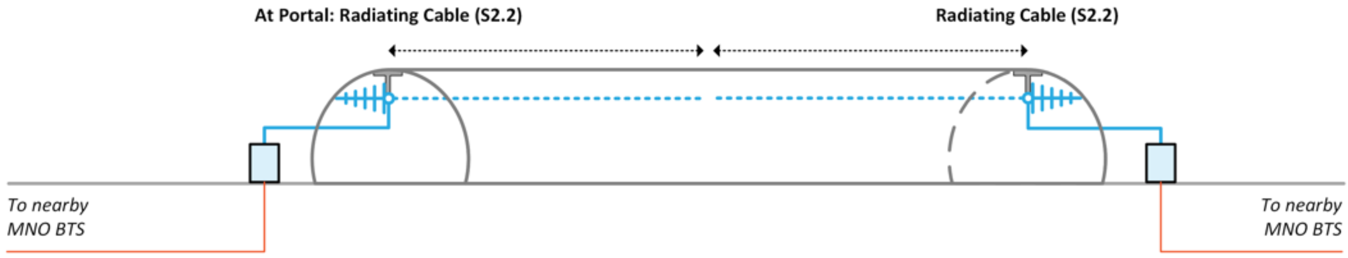


Figure 20c) - Tunnel fitment configuration options: S2.2 At Portal radiating cable (700-3,600 MHz)

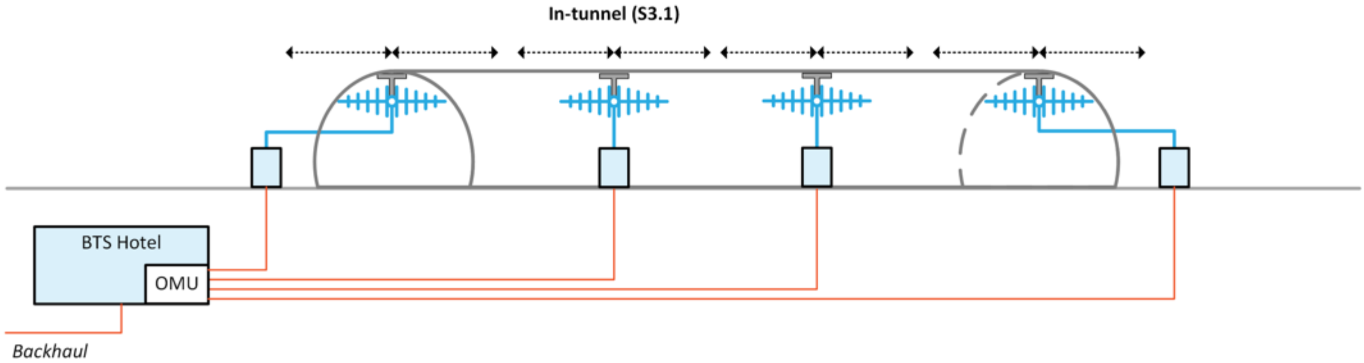


Figure 20d) - Tunnel fitment configuration options: S3.1 In-Tunnel directional antennas (700-3,600 MHz)

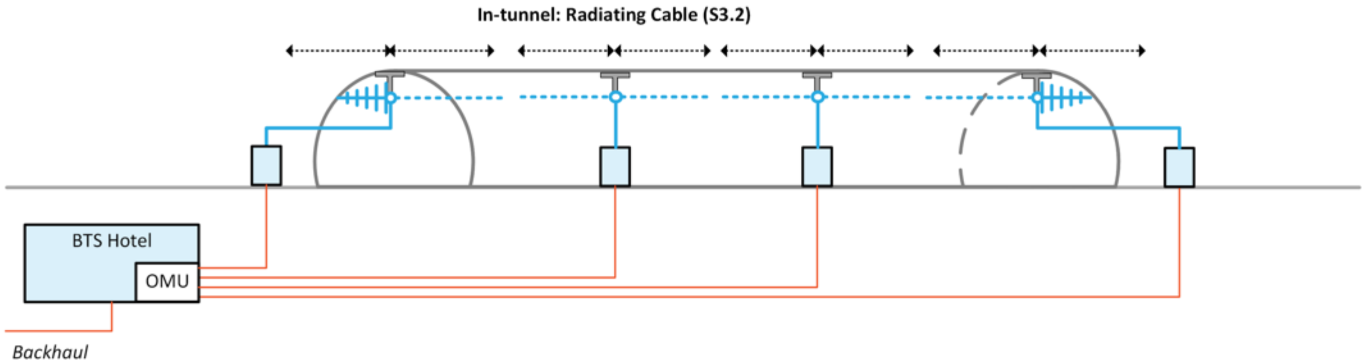


Figure 20e) - Tunnel fitment configuration options: S3.2 In-Tunnel radiating cables (700-3,600 MHz)

‘Near Portal’ (S1) (Figure 20a) and ‘At Portal’ (S2.1) solutions, using directional antennas (Figure 20b), or ‘In-tunnel’ (S2.2) solutions, using radiating cables (Figure 20c), combine individual MNO RRUs in a shared remote-control frame (Figure 21). A local 230V ac mains supply is converted by a shared power supply unit into 48V dc feeds for the MNO RRUs. Each MNO RRU also connects to a nearby MNO BTS via optical fibre cable links.

Each MNO RRU also transmits and receives an RF feed which is combined with those of the other MNOs’ RRUs to feed the directional antennas and/ or radiating cables via a shared RF power combiner.

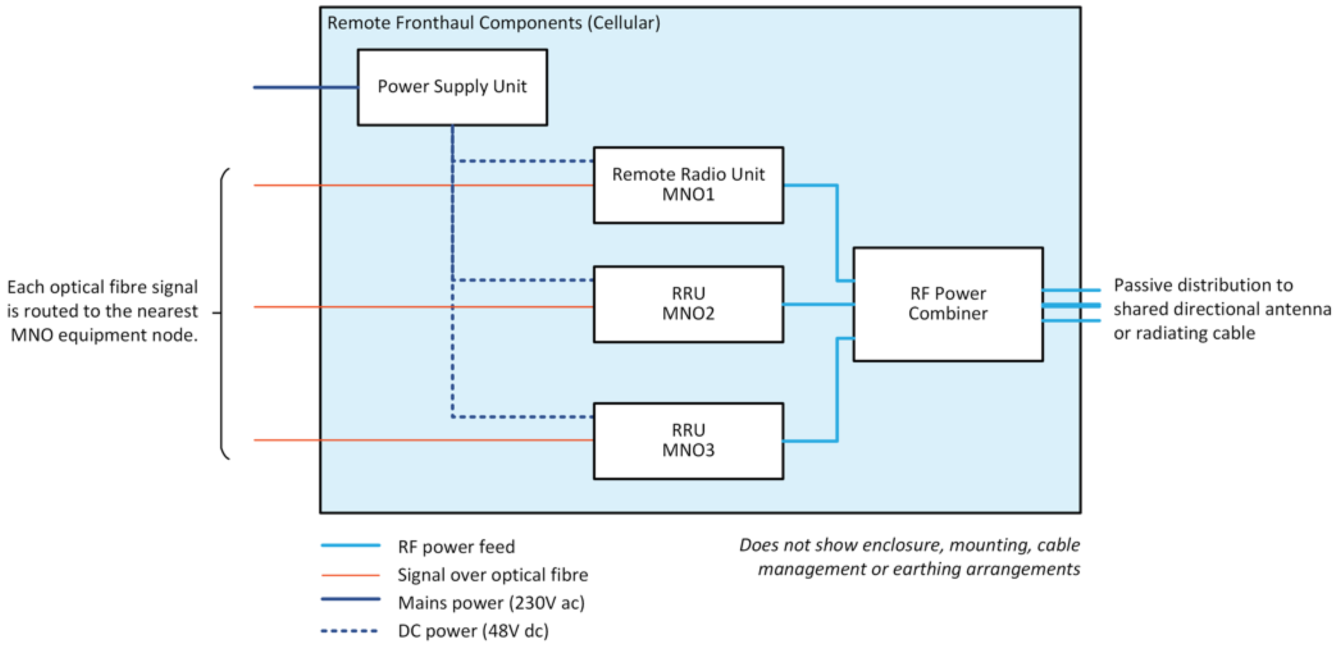


Figure 21 - Typical shared remote-control frame: Cellular frequencies

Figure 22 shows a specific example of a remote-control frame for an S2.2 ('At Portal' radiating cable) application feeding three active RF devices, a pole mounted outward facing antenna plus two RF feeds for radiating cables.

This example shows an installation mounted outside on a frame with cable trays above a tunnel portal. The RRUs are protected within rugged weatherproof IP67 enclosures. Spare fibre cable is protected within a circular organiser and terminated at a splicing box. A common earthing bar plus surge arrester provides surge and lightning protection. Wall mounting brackets support the pole carrying the outward-pointing directional antenna.

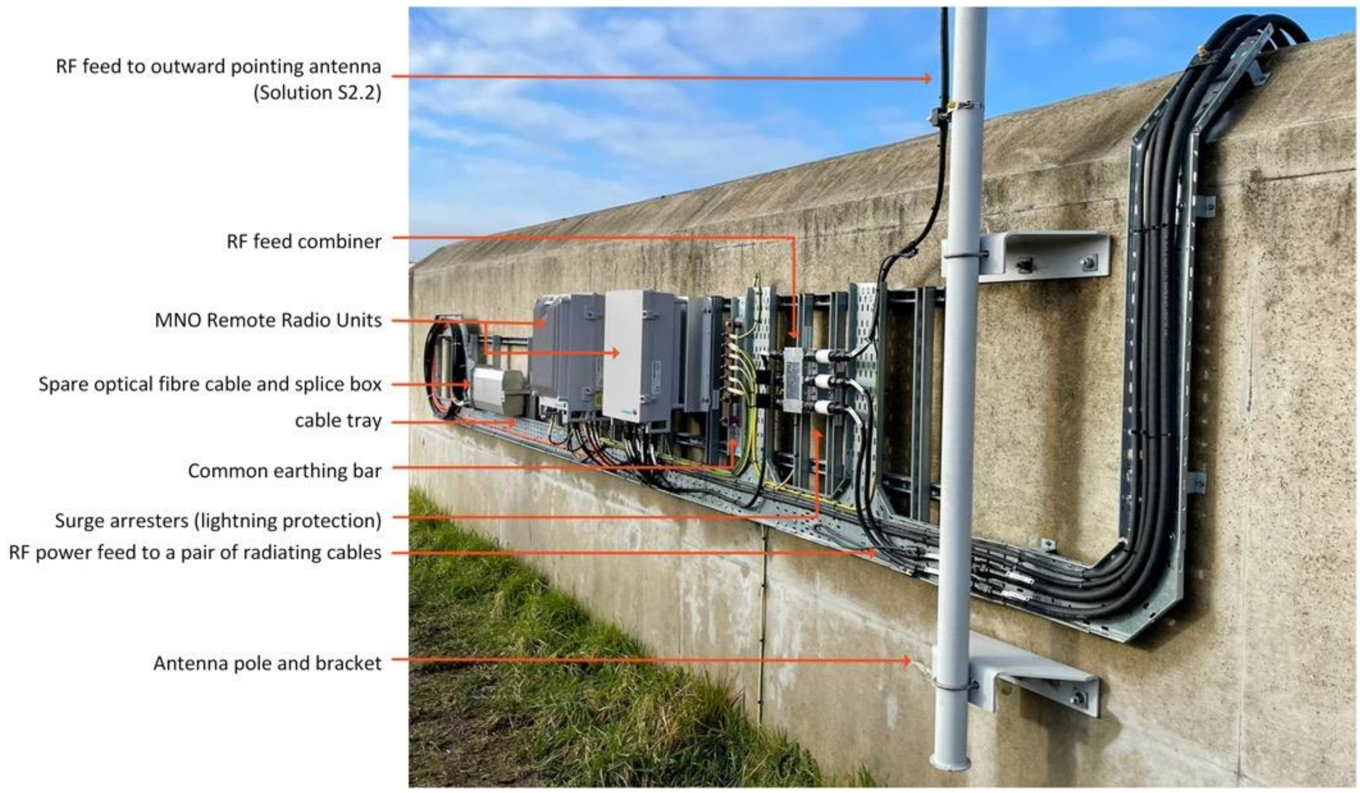


Figure 22 - S2.2: Typical remote control frame and RF feed arrangements to outward pointing antenna / radiating cable feeds

Figure 23 shows an example of a S3.1 ‘In-tunnel’ antenna with its feed arrangements. In-tunnel installations are only feasible if there is sufficient space to fit the antennas and control systems such as at the base of the tunnel wall, under a walkway, or at a refuge or cross-passage. These spaces may already have been occupied by other plant or cables.

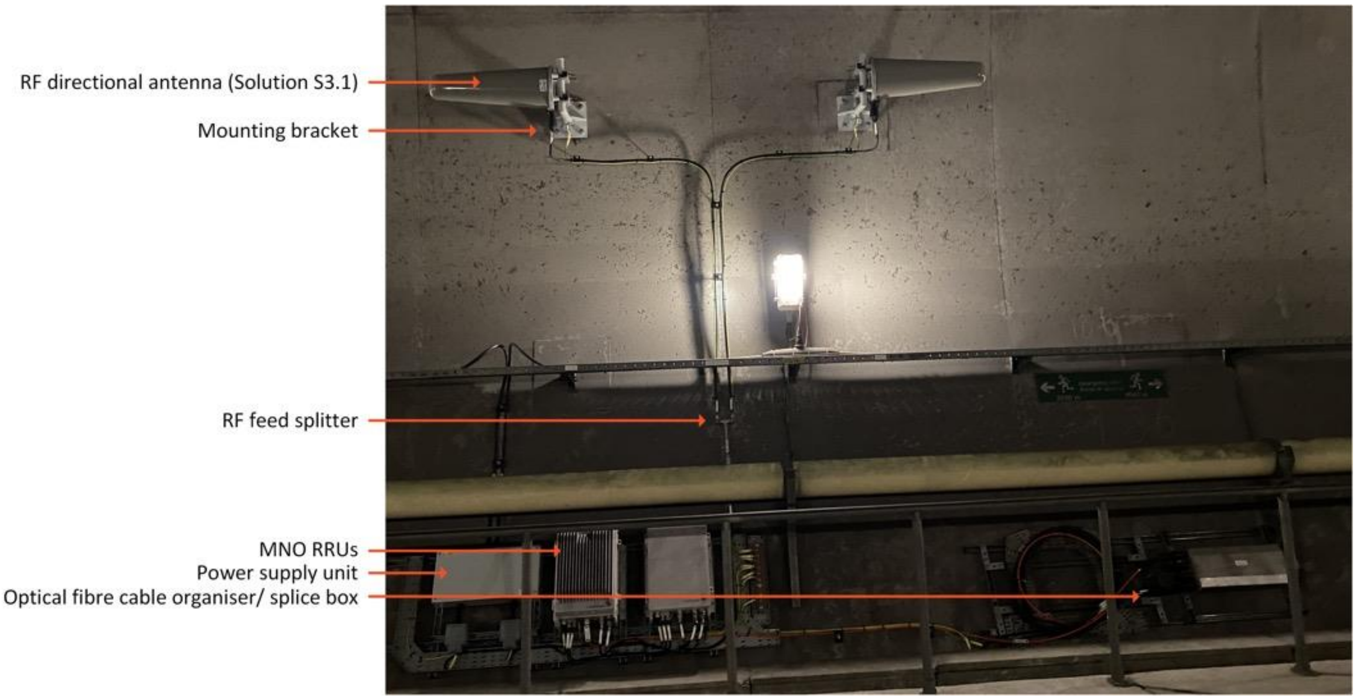


Figure 23 - S3.1 – Example cellular in-tunnel feed arrangements

The optical fibre links to each of these elements S3.1 (Figure 20d) or radiating cable S3.2 (Figure 20e) must be integrated with each other and other S2 portal elements at an OMU within a nearby BTS Hotel.

8.1.2 Comparison of practical deployment considerations – Cellular frequencies

Table 22 compares practical deployment considerations of each fitment configuration at cellular frequencies.

Parameter	**S1 Near Portal Directional Antenna**	**S2.1 At Portal Directional Antenna**	**S2.2 At Portal Radiating Cable**	**S3.1 In-tunnel Directional Antenna**	**S3.2 In-tunnel Radiating Cable**
Mast footprint	2.5m x 2.5m	NA	NA	NA	NA
Mast Location	30-60 metres from portal	NA	NA	NA	NA
Mounting structures: - Mast	8m monopole	NA	NA	NA	NA
- Space for active radio equipment (Figure 22 and 23)	[As provided for mast or as for S2.1]	4m x 2m for slab base within 20m of tunnel portal	4m x 2m for slab base within 20m of tunnel portal	Space alongside of tunnel floor, below walkway, with in refuge or cross-passage	Space alongside of tunnel floor, below walkway, with in refuge or cross-passage
Directional Antenna placement/ positions	Back-to-back	Back-to-back	Outward facing only	Back-to-back	NA
- Single track tunnels	As Figure 11 Height 5-6 metres above ground level	10 o’clock or 2 o’clock	10 o’clock or 2 o’clock	10 o’clock or 2 o’clock	NA
- Dual track tunnels	Same	11 o’clock or 1 o’clock	11 o’clock or 1 o’clock	11 o’clock or 1 o’clock	NA

Parameter	S1 Near Portal Directional Antenna	S2.1 At Portal Directional Antenna	S2.2 At Portal Radiating Cable	S3.1 In-tunnel Directional Antenna	S3.2 In-tunnel Radiating Cable
- Outward facing antenna	As high as possible with path clear of obstructions	NA	NA	NA	NA
Radiating Cable: 500mm wide section of wall space along the full length of the tunnel to install a pair of 1.625-inch diameter radiating cables, offset from the wall by 50mm and at least 100mm clear of metalwork	NA	NA	Yes 9-10 o'clock or 1- 2 o'clock	NA	Yes 9-10 o'clock or 1- 2 o'clock
Power consumption per active equipment unit.	Up to 2,000 W	Up to 2,000 W	Up to 2,000 W	Up to 650 W	Up to 650 W
Fronthaul connectivity between:					
- Active radio equipment and MNO BTS or shared hotel	Optical fibre	Optical fibre	Optical fibre	Optical fibre	Optical fibre
- RF feed to antenna	Co-axial copper	Co-axial copper	Co-axial copper to radiating cable	Co-axial copper	Co-axial copper to radiating cable
Frequency bands supported	700 MHz to 3,800 MHz	700 MHz to 3,800 MHz	700 MHz to 3,800 MHz	700 MHz to 3,800 MHz	700 MHz to 3,800 MHz
Frequency band to avoid (current GSM-R allocation)	900 MHz	900 MHz	900 MHz	900 MHz	900 MHz
Compliance with NR technical standards including:					
- NR/L2/TEL/3066 [52] for separation and clearances of fixed radio frequency transmitters	Yes	Yes	Yes	Yes	Yes
- NR/ L2/TEL/30034 [53] for earthing and bonding and lightning protection.	Yes	Yes	Yes	Yes	Yes
- NR/SP/ELP/21085 [54] on ac electrified railways	Yes	Yes	Yes	Yes	Yes

* Requires train fitted with external antenna and on-board gateway

Table 22 - Suitability of blueprint architectures by connectivity and carrier frequency: Cellular frequencies up to 4GHz

8.2 Tunnel wireless fitment design at higher frequencies

Radiating cables will not work at higher frequencies needed for wifi and mmWave applications, 5 to 60 GHz. Directional antenna solutions become simpler as they may be integrated and packaged as a much smaller integrated active antenna unit requiring only mains power and optical fibre feed that can be mounted on a pole or tunnel wall.

8.2.1 Configuration Options

Figures 24a) to 24c) show how the blueprint architecture elements (S1, S2.1, and S3.1) introduced in Section 7.2 (Figures 12a, b and c) may be configured using active antennas to fit a specific railway tunnel at higher frequencies.

The base scope is assumed to include active antennas, plus the power and optical fibre cables needed within the tunnel (which are variable costs dependent on tunnel length). Longer tunnels requiring S3 in-tunnel elements also include provision for an Optical Master Unit (OMU) at a BTS hotel and laying optical fibre connections of up to 1 kilometre through existing cable routes, ducts or troughs.

Although the tunnel active antennas may be cheaper to install than for cellular frequencies there may be additional commercial costs. Active antennas may not be supplied or supported by MNOs so there are likely to be additional costs obtaining commercial agreement and technical solutions to interface with MNO networks (see Section 9.1).

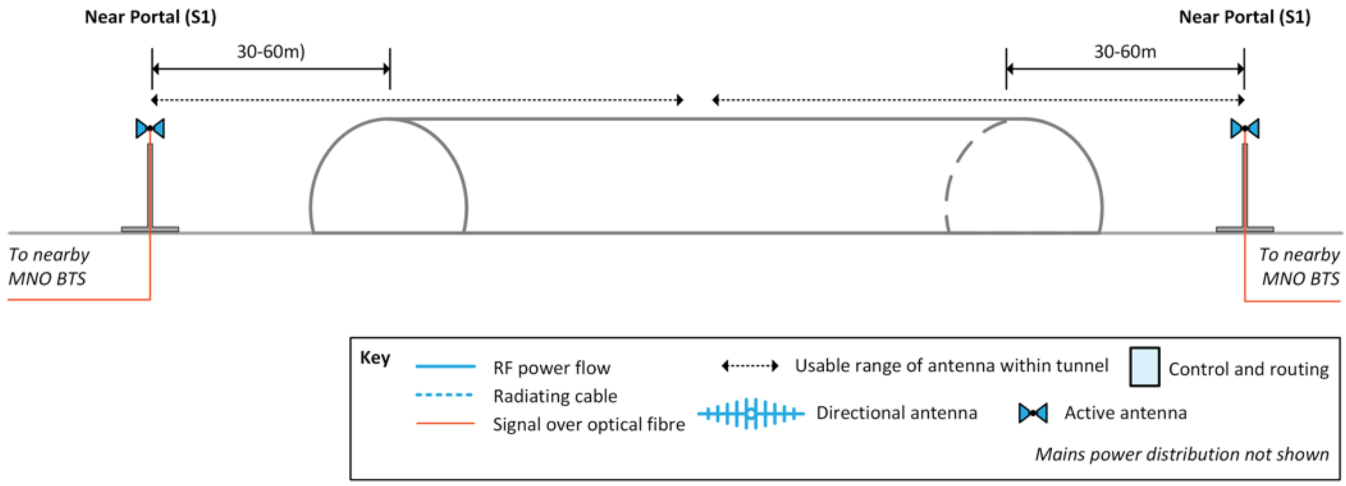


Figure 24a) - Tunnel fitment configuration options at higher frequencies, integrated active antennas: S1 Near Portal (active antenna)

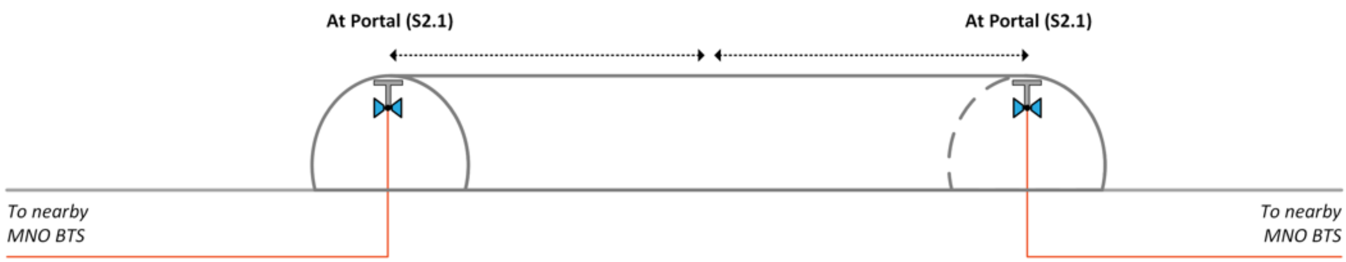


Figure 24b) - Tunnel fitment configuration options at higher frequencies, integrated active antennas: S2.1 At Portal (active antenna)

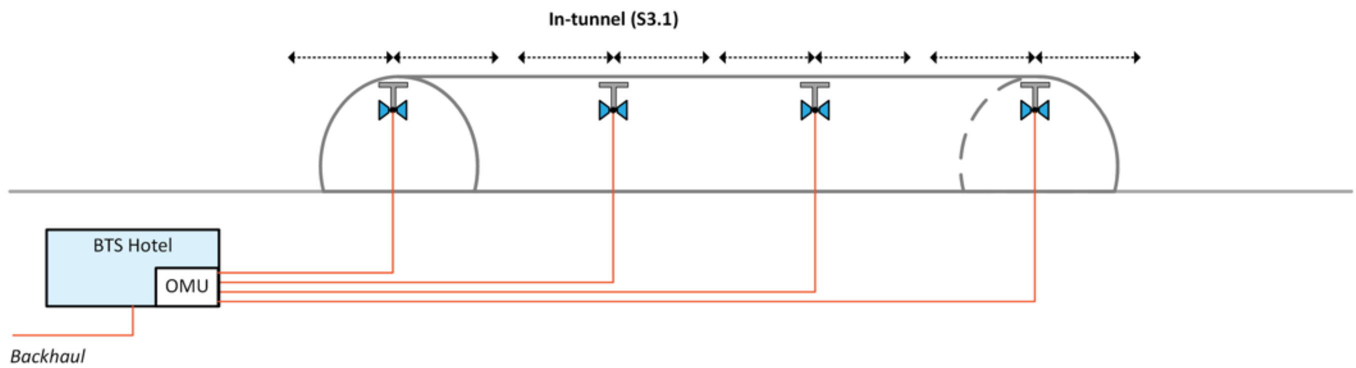


Figure 24c) - Tunnel fitment configuration options at higher frequencies, integrated active antennas: S3.1 In-tunnel (active antenna)

8.2.2 Comparison of practical deployment considerations – Higher frequencies

Table 23 compares practical deployment considerations of each fitment configuration option at higher frequencies using active antennas. Solutions S2.2 and S3.2 are ruled out as the frequencies are beyond the capabilities of radiating cable (Section 7.3).

Parameter	**S1 Near Portal Active Antenna**	**S2.1 Portal Active Antenna**	S2.2 Portal Radiating Cable [not applicable]	**S3.1 In-Tunnel Active Antenna**	S3.2 In-Tunnel Radiating Cable [not applicable]
Mast footprint	2.5m x 2.5m	Tunnel wall space for active antenna unit.		Tunnel wall space for active antenna unit.	

Parameter	S1 Near Portal Active Antenna	S2.1 Portal Active Antenna	S2.2 Portal Radiating Cable [not applicable]	S3.1 In-Tunnel Active Antenna	S3.2 In-Tunnel Radiating Cable [not applicable]
Mast Location	30-60m from portal	NA		NA	
Mounting structures: - Mast	8m monopole	NA		NA	
Antenna placement/ positions	Back-to-back integrated design	Back-to-back integrated design		Back-to-back integrated design	
- Single track tunnels	As Figure 11 Height 4-8m above ground level	10 o'clock or 2 o'clock		10 o'clock or 2 o'clock	
- Dual track tunnels	Same.	11 o'clock or 1 o'clock		11 o'clock or 1 o'clock	
- Outward facing antenna	Clear line of sight along track				
Power consumption per active equipment unit.	Up to 200W	Up to 200W		Up to 200W	
Fronthaul connectivity between:					
- Active radio equipment and BTS hotel.	Optical fibre direct to each active antenna head	Optical fibre		Optical fibre	
- RF power feed to antenna	N/A (integrated)	Co-axial copper		Co-axial copper	
Frequency bands supported	5 GHz (Wifi) 26 GHz, 67 GHz (mmWave)				
Compliance with NR technical standards including:					
- NR/L2/TEL/3066 [52] for separation and clearances of fixed radio frequency transmitters	Yes	Yes		Yes	
- NR/ L2/TEL/30034 [53] for earthing and bonding and lightning protection	Yes	Yes		Yes	
- NR/SP/ELP/21085 [54] on ac electrified railways - and (ac electrified railways)	Yes	Yes		Yes	

Table 23 - Suitability of blueprint architectures by connectivity and carrier frequency: Integrated active antennas 5–60 GHz

9 Relative cost model and tunnel fitment solution option selection

This section explains how fitment costs have been treated to devise a basic option selection tool to help potential sponsors realise their tunnel wireless connectivity requirements.

It describes how the study has identified relative unit costs and populated them within lookup tables. It then describes how these cost lookup tables may be combined with the usable signal propagation range tables from Section 7.6 and the configuration of different 'blueprint' architecture elements to aid high level option selection.

Several worked examples are included to illustrate how to apply the tables and to offer immediate insights that may help narrow down the choices further.

9.1 Commercial context

The aim of this study has been to improve understanding of wireless signal propagation within rail tunnels and show how this may influence the choice of wireless connectivity solutions, especially the most promising application designs at a high-level option selection to fit a specific tunnel. This is the basis of the option selection tool described in this Section 9. However, the wider commercial context must be considered as part of any eventual fit out.

To note, the relative cost modelling in this study excludes costs associated with the wider commercial context.

Scaling up and true cost of entry for disruptive technologies

The study concentrates on the fitment of a single tunnel. However, route or nationwide fitment needs to consider the wider feasibility and economy of fitment strategies. These apply to at least two cases directly relevant to this study:

- Relative cost comparison of direct versus indirect connectivity solutions should consider the route or nationwide cost of fitting both tunnels and affected fleets.

- New entrant network connection costs for innovative mmWave solutions may offer cheap tunnel fitment costs but not fitment along the full line of route. There is also the commercial challenge of persuading MNOs, recovering the costs of expensive licences and networks, to sell seamless network connections at a reasonable price.

DfT and other stakeholders need to understand the combined cost to understand the opportunities for economies of scale.

Stakeholders - commercial obligations and opportunities

It is not clear who should finance the aspiration of good connectivity for rail passengers (Section 1) especially given the number of stakeholders and uncertain commercial drivers and benefits.

MNOs have some obligation to improve direct connectivity as part of their licence conditions, but these do not extend to the railways. Likewise, NR facilitate improvements to the railway infrastructure and maintain their own critical mobile infrastructure for operational reasons, but this is unrelated to passenger requirements. And although the train operators have specific and committed obligations to deliver on-train wifi the costs of dedicated trackside infrastructure can be high particularly as they wish to deliver a whole of journey experience.

In the absence of obvious commercial opportunities, MNOs, NR and train operators look to each other to find the funds. This problem is likely to get worse as the cost and complexity of wireless coverage of the railway increases and passenger mobile connectivity expectations increase.

Technical complexity and procurement challenge

Sections 3-8 of this report have shown that extending wireless connectivity to rail tunnels and deep cuttings is challenging and technically complex, especially if on-train gateways prove central to meeting the demand for data capacity to offer a good experience to most passengers.

A procurement strategy is needed to bring stakeholders together to resolve the many complex system and operational integration challenges but is beyond the scope of this study. For example, this study does not attempt to assess the commercial challenge or costs for mmWave promoters to integrate their active antenna networks with those of MNOs. This challenge is also recognised in the 'Carriage Attenuation' report [6] by the Arup Alliance.

Tunnel wireless connectivity as enhancement to the existing railway

The cost estimates in this section do not consider the cost of additional enabling works to integrate new wireless connectivity into the existing railway, such as:

- Civil or structural works to generate space for wireless equipment or asset repairs and renewals to improve their condition.
- Diversion of existing services to make space for wireless equipment and restore it post-installation.
- Removal and recovery of obsolete services or assets to make space for new wireless infrastructure.
- Inefficiencies because of sub-optimal siting of wireless equipment.
- Inefficiencies as the result of elaborate stage works to install the new services without disrupting normal railway operations.

Unexpected through life costs

The cost estimates in this section do not consider the cost of unexpected through-life costs enforced by the supplier, such as equipment or software upgrades because of declared obsolescence or urgent changes to standards.

Project Management, supervision and assurance by the Infrastructure Manager

The cost estimates in this section do not include the additional costs of working in accordance with the project management procedures, gateways and assurance or supervision requirements of the railway infrastructure manager, its Network Statement, and its contractors, for example:

- NR Governance of Railway Investment Projects (GRIP) setting out decision gateways, review processes and minimum design, installation, commissioning, and assurance documentation.
- NR business and procurement processes.
- NR company standards.
- Rail industry network statement and Network Code change management mechanisms that also control engineering access to the railway.
- ORR Safety Regulatory interventions (ROGS and RIR) and NR internal safety assurance processes.
- Achievable possession productivity.
- Frustrated access when a booked possession is withdrawn at the last minute because of a change to operational or maintenance priorities.

Few MNOs have experience of working in such a rail environment and the additional costs and timescales involved.

9.2 Purpose of relative cost comparator

As part of a high-level option selection tool, the main aim of the relative cost comparator is to help discriminate between the alternatives and opportunities to optimise the configuration of solutions. For example:

- The difference in benefit between a single or dual radiating cable solution, or

- Trade-offs between minimum signal power coverage and tunnel fitment costs.

The cost model is not expected to assess the prior configuration or condition of any existing railway tunnel, but it should be able to indicate the costs needed to fit out a tunnel assuming a ‘clean slate’ site. Precision is intended to be ±10% at best so unit costs need only be stated to two significant digits.

As Section 9.1 has discussed there may be large costs linked to the way the investment is funded, managed, and delivered but these are beyond the scope of this study and common to all the wireless tunnel fitment solutions. There may be other cost elements to ignore that are difficult to estimate but not relevant to discrimination between the options.

The aim is to offer some insight as to whole life cost by estimating annual operation and maintenance costs for the systems supplied as a proportion of capital cost, typically 12% of capital cost.

9.3 Cost Elements used to model tunnel fitment costs

The cost of a complete tunnel fitment solution is compiled from unit cost elements: Figures 25a) through c):

- **Unit costs** (CS1, CS2.1, CS2.2, CS3.1 and CS3.2) for each blueprint architecture element (S1, S2.1, S2.2, S3.1, S3.2) identified in Figures 20 a) through e) and Figures 24a) through c) – there may be multiple CS3.1 and CS3.2 elements, especially to address very long tunnels,

- **Additional variable costs per tunnel km** (CV3.1) to reflect the cost of additional power cables and optical fibre cables to connect the CS3.1 or CS3.2 in-tunnel elements,

- **Additional variable costs per tunnel km** (CV3.2) to reflect the cost of fitting radiating cable to tunnels to support both CS2.2 portal or CS3.2 in-tunnel elements, and

- **Additional one-off fixed cost** (CF3) needed to fit an Optical Master Unit at a multi-MNO BTS hotel and route optical fibre cable to up to 1 kilometre away.

The configuration of cost elements is the same for cellular directional antennas (Figure 25a) and higher frequency integrated active antennas (Figure 25b). The radiating cable options (Figure 25c) are only suitable at cellular frequencies.

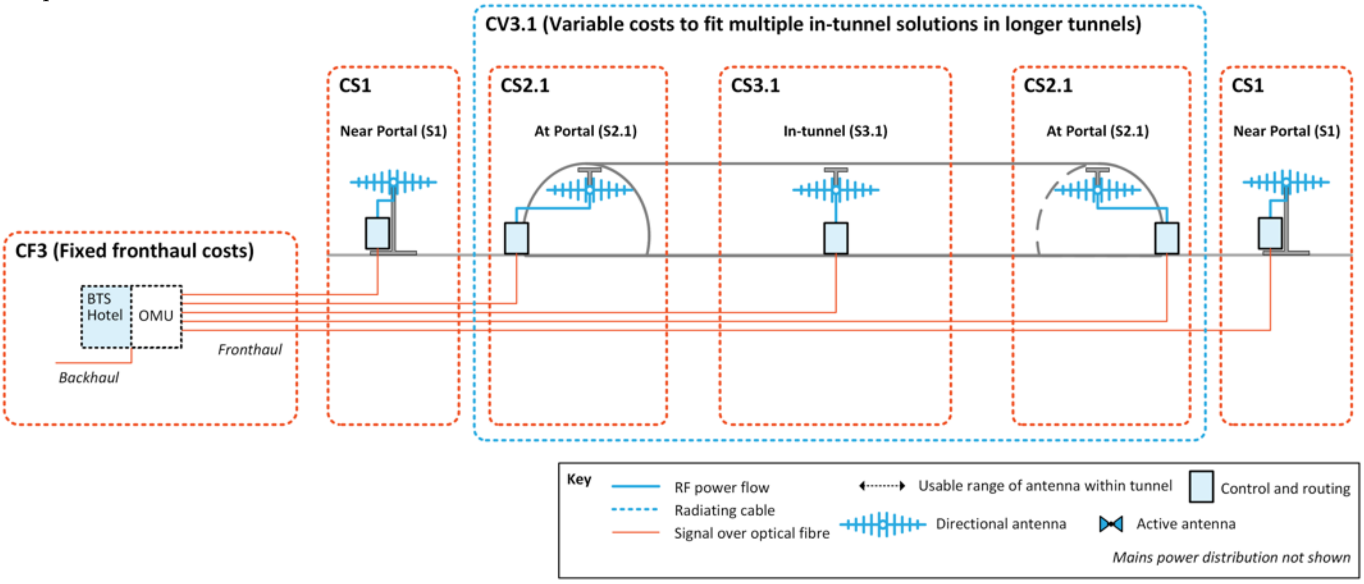


Figure 25a) - Directional Antenna fitment unit, variable and fixed cost elements: cellular frequencies up to 3,600 MHz

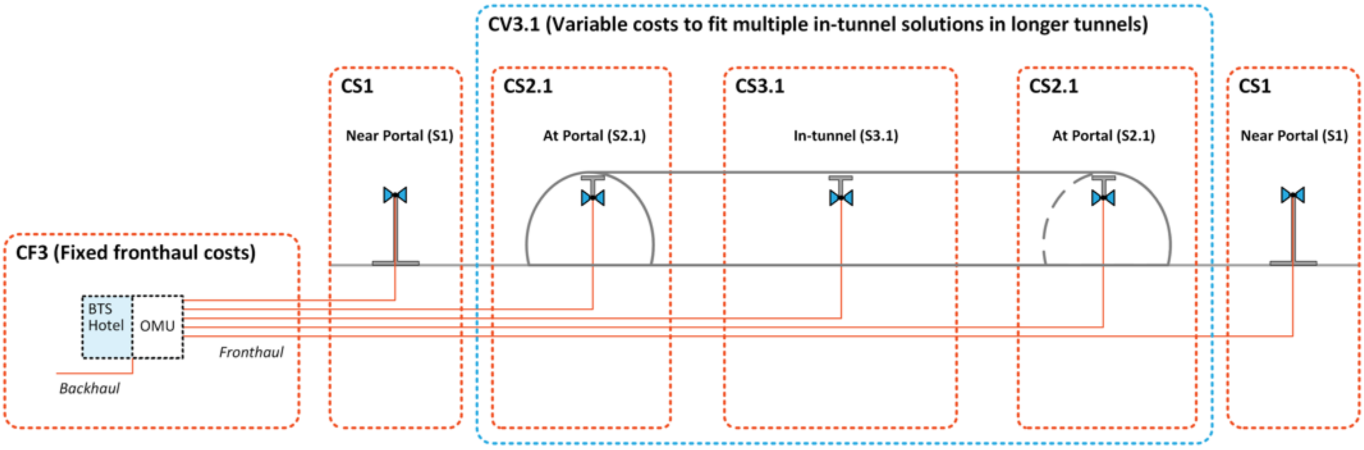


Figure 25b) - Active Antenna fitment unit, variable and fixed cost elements (5-60GHz)

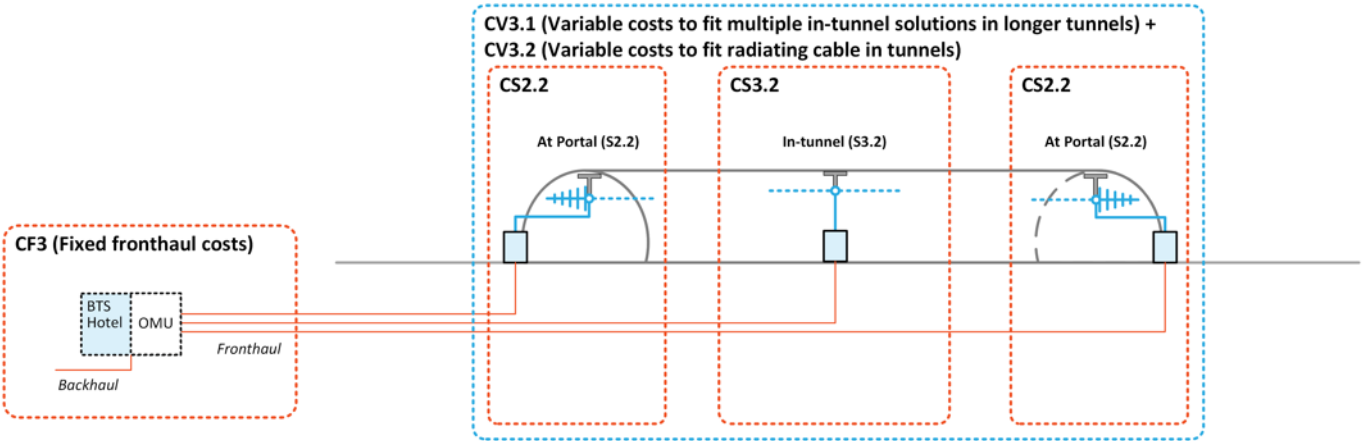


Figure 25c) – Radiating cable fitment unit, variable and fixed cost elements: cellular frequencies up to 3.6 GHz

Table 24 lists the eight (cellular) and five (higher frequency) cost elements and the tunnel fitment solutions to which they apply.

Fitment Cost Element	Fronthaul Cost Element included within different fitment solutions	Fitment solution(s) Cellular Sub-4 GHz	Fitment solution(s) mmWave 5-60 GHz
CS1	Near portal (mast, radio kit and antennas) Excludes MNO RRUs (free issued)	S1	S1
CS2.1	Portal, directional antennas (radio kit) Excludes MNO RRUs (free issued) and antennas)	S2.1, S3.1	S2.1, S3.1
CS2.2	Portal, radiating cables (radio kit) Excludes MNO RRUs (free issued) Excludes Radiating cable (see variable CV3.2)	S2.2, S3.2	NA
CS3.1	In-tunnel, directional antennas (shared radio kit, antennas) Includes shared RRU at cellular frequencies Excludes fixed CF3 and variable CV3.1 elements	S3.1	S3.1
CS3.2	In-tunnel, directional antennas (shared radio kit) Includes shared RRU at cellular frequencies Excludes fixed CF3 and variable CV3.2 elements	S3.2	NA
CF3	Fixed BTS Hotel cost for in-tunnel (DAS) solutions Includes OMU installed within an MNO BTS hotel Includes up to 1km optical cable link to BTS Excludes all other equipment (MNOs' responsibility)	S3.1, S3.2	S3.1

Fitment Cost Element	Fronthaul Cost Element included within different fitment solutions	Fitment solution(s) Cellular Sub-4 GHz	Fitment solution(s) mmWave 5-60 GHz
CV3.1	Variable (dependent on Tunnel length) to cover the cost of power and optical fibre connections to each in-tunnel directional antenna (CS3.1, CS3.2).	S3.1, S3.2	S3.1
CV3.2	Variable (dependent on Tunnel length) to cover the cost of radiating cable to each in-tunnel radiating cable element (CS3.2)	S2.2, S3.2	NA

* Requires train fitted with external antenna and on-board gateway

Table 24 - Blueprint architecture unit, variable and fixed cost elements and associated tunnel fitment solutions

9.4 Relative cost breakdown structure and exclusions

Table 25 lists the cost items included in the cost comparator model introduced in Section 9.2.

Costs included	Relevant Cost Element	Comments
Antennas	CS1, CS2.1, CS3.1	Including integrated antenna amplifiers.
Radiating cable	CV3.2	Use also for CS2.2 and in addition to CV3.1 Treated as a separate variable cost per tunnel km.
Remote frame to accommodate RRU, power supplies, combiners and other passive RF distribution components	CS1, CS2.1	Excludes the cost of MNO RRU modules (assumed supplied free issue by MNOs).
In-tunnel active RF equipment (includes cost of local RRU)	CS3.1, 3.2	In-tunnel the shared RRU that links the in-tunnel element to the shared OMU at the MNOs' BTS Hotel for connection to MNO networks;
Connectors	All CS elements	• RF power link, • LV mains power and • Optical fibre cables
Surge arrestors	All CS elements	Lightning protection.
RF signal feed cables (up to 10m long)	Most CS elements	Between Remote Radio Unit amplifiers and passive directional antennas (cellular frequencies only).
RF Combiners (3+ way)	CS1, CS2,1, CS2,2	Shared JOTS antenna connected to at least 3 MNO feeds.
RF Splitter (2 way)	CS3.1	In-tunnel directional antennas connected to shared RRU (much cheaper than an RF combiner) (cellular frequencies only).
Selected Optical fibre cables; • CS3 to in-tunnel elements • CF3 to OMU in BTS hotel (up to 1km)	CS3.1, CS3.2, CF3, CV3.1	BTS hotel distribution frame to remote radio units or integrated active antennas.
Selected Mains power cables: • To CS3 in-tunnel elements • Tails to local mains supplies	CS3.1, CF3, CV3.1	
Selected civil/ structural and mechanical/ electrical elements: • Rapid deployment pole and base • Concrete pads for mounting of CS, CV3 and CF3 elements	CS1	
Cabinets and enclosures	CS1, CS2.1, CS2.2	Located and mounted within containment already available or supplied by others
Lineside mast and base	CS1	
Mounting brackets	All CS packages	• Antennas to poles or surfaces • Radiating cables to tunnel surfaces
Optical Master Unit (OMU)	CF3	OMU and its equipment rack
Direct labour costs for installation	All CS elements	Installation, test and commissioning (assuming productivity of 4 hrs per overnight possession).

Costs included	Relevant Cost Element	Comments
Indicative annual operating and maintenance costs (OPEX): • Power consumption • Maintenance support of CS, CV3.1, CV3.2 and CF3 systems	All CS elements	As proportion of initial capital expenditure (CAPEX), typically 12%

Table 25 - Costs included within relative cost model

Table 26 lists costs excluded from the model that also excludes those discussed in Section 9.1.

Costs Excluded	Comments
All MNO backhaul systems	• Connections within MNO networks, including equipment rooms, enclosures, BBU, RRU, cable ways, troughs and ducts, LV mains and optical fibre cable • Dedicated MNO RRUs
Commercial context (Section 9.1) including: • Preliminaries • Design assurance & approvals • Possessions and access • Through life upgrades	
Mechanical & Electrical Costs	Site containment provision and earthing and bonding
Civil & structure costs	• Ducting/ troughing • Adequate size and asset condition of containment and surface mounting points
All other operating and maintenance costs (OPEX): • E&M (power, optical fibre, heating, ventilation and air conditioning, SCADA) • Civils and structures	

Table 26 - Costs not included within the relative cost model

9.4.1 Other assumptions of the cost model

This study has devised a simple cost model to compare the relative scale of direct tunnel fitment costs for high level option selection and budgeting. Precision is not intended to be better than ± 10% so unit costs are only stated to two significant digits. Other assumptions include:

- A night shift comprises 4 persons performing up to 4 hours of active working times.
- Core network infrastructure system signalling control is already provided as part of the wider solution.
- New optical fibre and power cables will be pulled to S3 installations within the tunnel from the tunnel portal.
- mmWave equipment will be supplied as integrated "all-in-one" active antenna units comprising radio control and antennas.

9.5 Relative cost model

9.5.1 Unit, fixed and variable cost estimates

Table 27 provides indicative unit, variable and fixed costs for comparison of the elements described in Section 9.3.

Unit Costs	Fronthaul Cost Element	Cost (£) Cellular Sub-4 GHz	Cost (£) mmWave 5-60 GHz
CS1	Near portal	79,000	66,000
CS2.1	Portal, directional antennas	53,000	35,000

CS2.2	Portal, radiating cable (active RF drive but not cable) Excludes the variable cost of the radiating cable itself!)	49,000	NA
CS3.1	In-tunnel, directional antenna, shared radio kit plus antenna (Excludes fixed CF3 and variable costs CV3.1)	47,000	35,000
CS3.2	In-tunnel solution, radiating cable (shared radio kit) (Excludes fixed CF3 and variable costs including the radiating cable CV3.2 itself)	36,000	N/A
CF3	Fixed cost of Optical Master Unit at MNO BTS Hotel plus the optical link for longer tunnels requiring in-tunnel solutions (DAS)	66,000	Unknown
CV3.1	Variable cost of services installed with the tunnel to support in-tunnel CS3 solutions • LV mains Power cables • Optical fibre cable	50,000 (per tunnel km)	50,000 (per tunnel km)
CV3.2	Variable cost of radiating cable installed within the tunnel to support CS2.2 or CS3.2 solutions	150,000 (per tunnel km)	N/A

Table 27 - Unit, fixed, and variable cost estimates

It should be noted that the unit costs shown in Table 27 mean little in isolation until they are combined with fixed and variable costs, especially for radiating cable and longer tunnels:

- Radiating Cable solutions need to combine the unit cost elements CS2.2 and CS3.2 with the variable cost of fitting radiating cable CV3.2 throughout the tunnel.
- In-tunnel solutions need to combine multiple unit cost elements CS3.1 and CS3.2, the fixed cost of CF3 OMU connections plus the variable cost of LV mains power and optical fibre cable (CV3.1) throughout the tunnel.
- In-tunnel solutions also assume CS2.1 or CS2.2 elements at each portal.

9.5.2 Dependence of cost model on tunnel length and usable signal propagation range

The tunnel fitment cost model is also dependent on tunnel length and the usable signal propagation range of each ‘blueprint’ architecture elements.

Tunnel Length **d** (km) to calculate the variable costs of tunnel LV mains power, optical fibre cable (CV3.1) and installed radiating cable (CV3.2).

Number **n** of in-tunnel elements (CS3.1 or CS3.2) needed to provide coverage throughout the tunnel. This can be calculated using the tunnel length d and the usable range r of each blueprint propagation element (Section 7.6). By assuming r already makes adequate provision for cell handover and is the same for portal and in-tunnel elements.

n is either 0 or the first integer greater than or equal to: $\mathbf{n \geq (d/2r) - 1}$ .... [Eq.9-1]

Table 28 shows the unit, variable, and fixed cost multipliers using tunnel length **d** and usable signal range **n** needed to calculate total fitment costs from the unit, variable and fixed costs (Table 27) whole tunnel fitment costs for tunnel solutions S1, S2.1, S2.2, S3.1 and S3.2.

Number of blueprint unit cost multipliers	S1 Near Portal	S2.1 Portal Directional antenna	S2.2 Portal Radiating Cable	S3.1 In-Tunnel Directional Antenna	S3.2 In-Tunnel Radiating Cable
CS1	2	-	-	-	-
CS2.1	-	2	-	2	-
CS2.2	-	-	2	-	2
CS3.1	-	-	-	**n**	-
CS3.2	-	-	-	-	**n**

CF3	-	-	-	1	1
CV3.1	-	-	-	**d**	**d**
CV3.2	-	-	**d**	-	**d**

Table 28 - Unit cost multipliers to calculate tunnel fitment costs

This multiplier table is just as valid for cellular frequencies as higher frequencies, for direct connectivity as indirect versus on-train gateways. The model adapts to each application because n is dependent not just on tunnel length **d** but also usable range **r** [Equation 9-1], noting **r** depends on many factors as discussed in earlier sections:

- Tunnel type, antenna type, and carrier frequency (Section 7.6).
- Data link application (Section 4.1) as the usable range **r** for direct passenger connectivity is reduced by additional train shadowing, vehicle penetration, and body losses, unlike an external train antenna connected to an on-train gateway (Section 6.2).
- Siting of 'Blueprint' architecture propagation elements 'Near Portal' (S1), 'At Portal' (S2) or 'In Tunnel' (S3) (Section 8.1).

This relationship will be used in the option selection process described in Section 9.6. However, a worked example is provided below to show how the tunnel fitment cost calculation works once the number of in-tunnel elements **n** has been determined.

9.5.3 Example relative cost calculation for a tunnel fitment when 'n' is known

This example calculates the cost of an S3.2 radiating cable fitment for a 5 kilometre tunnel, where the number of CS3.2 in-tunnel radiating cable elements, **n** is 5[iii] in addition to a pair of CS2.2 portal elements.

The cost model also includes the additional cost of an OMU (CF3), the cost of mains and optical fibres within the tunnel (CV3.1), plus the cost of installing radiating cable throughout (CV3.2).

Table 29 shows how the costs accumulate, applying the unit costs from Table 27 and the multipliers from Table 28 combine and accumulate to estimate the relative cost of whole tunnel fitment.

Cost Elements	**Unit cost (£)**	**Quantity**	**Cost (£)**	**Cumulative(£)**
CS3.2 In-tunnel radiating cable elements	36,000	5 units	72,000	72,000
CV3.1 LV power and optical fibre cable throughout tunnel	50,000/km	5 km	250,000	320,000
CV3.2 Radiating cable fitment throughout tunnel	150,000/km	5 km	750,000	1,100.000
CS2.2 Portal radiating cable elements	49,000	2 units	98,000	1,200,000
CF3 OMU at BTS hotel plus optical fibre link	66,000	1 unit	66,000	1,250,000
S3.2 overall tunnel fitment	**-**	**-**	**Total***	**1,300,000**
S3.2 Average cost per tunnel km	-	-		260,000/ km
S3.2 Average operation and maintenance cost per year	@12% Capex	-		160,000/ year

* Totals shown to two significant digits

Table 29 - Tunnel fitment relative cost calculation

This example suggests a 'rule of thumb' fitment cost with radiating cable is ~£250,000 per kilometre. This highlights why sponsors should use the unit costs in Table 27 with care.

It also offers an indication of whole life costs by calculating annual operational and maintenance expenditure as 12% of initial installation cost, £160,000 per year.

Table 30 compares typical expected tunnel fitment costs for the five solution types assuming indirect connectivity to an external train antenna and on-train gateway. The tunnel lengths that could support directional antenna solutions S1 and S2.1 vary with usable signal propagation range, with tunnel type, size, and carrier frequency. The usable range for S1 and S2.1 would be at least 80% shorter for direct connectivity, even if additional train losses do not exceed 15 dB.

Fitment	Tunnel fitment Examples	Tunnel Length (km)	Cost (£) Cellular Sub-4 GHz	Cost (£) mmWave 5-60 GHz
S1	Dual Ended Near Portal Solution	1.4-5*	160,000	130,000
S2.1	Dual Ended Portal Solution with Antennas	1-5*	105,000	70,000
S2.2	Dual Ended Portal Solution with Radiating Cable	1	850,000	NA
S3.1	In-Tunnel Solution with Antennas	5	550,000	420,000
S3.2	In-Tunnel Solution with Radiating Cable	5	1,300,000	NA

* Assumes indirect connectivity with on-train gateway. The maximum range varies with tunnel type, size and carrier frequency, 100mph cell handover

Table 30 - Indicative tunnel fitment relative costs

9.6 Tunnel fitment solution selection and comparison

This section considers the more general case where n needs to be calculated from a candidate tunnel of known length **d** and usable signal propagation range **r** [Equation 9-1], itself dependent on many other factors (Section 9.5.2). This allows the tunnel fitment cost to be estimated for any blueprint architecture option that is technically feasible and makes the sponsor aware of other practical deployment considerations. By repeating this analysis for a variety of options, sponsors may compare the costs, strengths, and weaknesses of each option to make a high-level selection.

The option selection and analysis process were first introduced in Figure 1 of Section 2.2. Table 31 works through each step to unpack each candidate tunnel scenario and analyse it with reference to the standard tunnel types, blueprint architecture propagation types and siting options and unit, fixed and variable cost assumptions that is the closest fit to the candidate tunnel. The model estimates usable signal propagation range from a limited selection of six standard tunnel types, for single and dual-track versions of brick arch, unlined rock, and segmental reinforced concrete tunnel designs. The sensitivity of outputs may also be assessed by triangulation, by selecting more than one of the standard tunnel types available for analysis. Sponsors can select from the results of whichever options they model. This is not an automated decision tool, just a helpful simple algorithm populated with useful data based on stated assumptions.

Sponsors will need to validate any findings by site surveys and detailed feasibility analysis. From a Network Rail perspective, this tool offers insights as input relevant to the GRIP 1 ‘Output Definition’ decision stage gate.

9.6.1 Option selection comparison for candidate tunnel wireless fitment scenario

The starting point is a candidate railway tunnel wireless fitment scenario (see box).

Example Railway Tunnel Wireless Fitment Scenario

Candidate tunnel: South Hampstead Tunnel – 1.1 km long straight dual-track bored brick arch tunnel.

Connectivity requirement: 20Mbps 5G service to passenger mobile devices from a 3,600 MHz carrier using an allocated bandwidth of 40 MHz, otherwise configured as detailed in Appendix 2.

Supply information to allow comparison of the following potential options:

a) Near portal antenna installed within 50 metres of the tunnel portal on a new mast installation, either by direct connectivity to rail passengers’ devices or indirectly by way of an external train antenna connected to an on-train gateway serving passenger devices throughout the train.
b) Radiating cable solution installed within the tunnel to offer a direct connection to passenger mobile devices.
c) Millimetric wave solution operating at 26 GHz by line of sight to an external train antenna.

Table 31 summarises how the option selection process guides the sponsor step-by-step, systematically analysing the candidate scenario and solution option under consideration, applying the structured lookup tables and simple relative cost model to generate assessment data for each option considered.

Option selection process to work through Candidate Scenario	Relevance to option selection	Application of lookup tables
1 Select tunnel for fitment	a) Length of tunnel b) Tunnel signal propagation characteristics: • Construction and lining material • Single or double track (size) • Cross-sectional profile • Alignment/ curvature c) Tunnel peak line speed will also determine the length of cell handover that allows 5 seconds for handover. Reduce usable range by half the cell handover distance	• Sets tunnel length **d** (km) • Select which of the six modelled (Section 3.3 and 7.6) **tunnel types** is the closest match – alternatively 'triangulate' for each of two or three of the tunnel types • Table 10 calculates handover distances for typical line speeds.
2 Select connectivity requirement [There may be several different connectivity scenarios to explore in turn, especially combinations of 2(c-e)]	a) Minimum target data rate b) Direct connection to passenger device or by way of on-train gateway. c) Wireless technology generation d) Allocated spectrum carrier frequency and signal bandwidth e) Special features of technology such as MIMO antennas, carrier aggregation, dynamic spectrum sharing or capacity optimisation.	• This sets the minimum target tunnel signal power level that in turn also sets the usable signal range of any antenna element. • The lookup tables for this study were populated by assuming a fixed minimum tunnel signal power level of -105dBm RSRP (Section 7.3.3). Sponsors may wish to select a different minimum signal power target.
3 Select 'blueprint' architecture fitment solution option	a) Signal propagation technologies • Directional antennas • Linear distributed radiating cable (cellular frequencies 700 MHz to 2,600 MHz only) • Integrated active antennas (High frequencies only 5 to 60 GHz) b) Antenna siting options • S1 Near Portal (not radiating cable) • S2 At Portal • S3 In-tunnel (signal reinforcement and coverage of longer tunnels)	• This is used to calculate the cost of tunnel fitment options and their basic feasibility and practicality. • The cost model populated with unit, fixed and variable costs may be used to calculate the fitment cost for a given length and usable signal range (Sections 9.3-9.5). • Some options may be ruled out as impractical.

Table 31 - Option Selection and Comparison algorithm

Option selection process to work through Candidate Scenario	Relevance to option selection	Application of lookup tables
4 Calculate the usable signal range r of the 'blueprint' architecture elements	The usable range is not just dependent on the antenna type and its orientation but also: a) Purpose of data link as additional train losses will reduce the usable range for direct connectivity to passenger devices b) Tunnel characteristics. c) Carrier frequency	• The usable range **r** has been calculated using the **signal range lookup tables** covering data link application, tunnel type, blueprint solution, and carrier frequency. • **Some options may be ruled out because of lack of range.**

Option selection process to work through Candidate Scenario		Relevance to option selection	Application of lookup tables
5	**Calculate the relative cost of tunnel fitment**	Cost is central to a business assessment of a tunnel fitment opportunity and selection between options. Several worked examples may also be used to establish 'rule of thumb' cost per km predictions of the different solution types.	• The value of **r** is also used to calculate **n** the number of in-tunnel blueprint elements, if any, to maintain signal coverage throughout longer tunnels. The usable range needs to include adequate provision for cell handovers (Section 6.5).
6	**Repeat for each option of interest**		
7	**Compare the options using the information generated by the option selection process.**	Sponsors can compare the performance, cost, technical feasibility, and practicality of the options analysed to identify the best trade-offs.	• The algorithm simply generates cost and feasibility information for each option explored. It is up to the user to compare the options and make the high-level selection. Sponsors will also need to validate any assumptions made.

Table 31 (cont.) - Option Selection and Comparison algorithm

Two practical worked examples that apply the option selection and comparison algorithm are presented in Section 9.7 and 9.8.

These also show that while it may be necessary to work through every step of the process for each tunnel fitment solution option considered, it may also be possible to pause at one of the sub-steps to work quickly through several alternative options. For example, there may be several permutations of carrier frequency and signal bands using carrier aggregation that could provide the required data rate, worth comparing immediately before proceeding to the next step in the process. The algorithm may also help the user to rule out by inspection many potential options without having to complete a full analysis.

Business sponsors may need to adapt the model and lookup table data presented in this study to reflect different assumptions. For example, this model assumes a minimum target signal power level within the tunnel of -105 dBm. However, sponsors may wish to examine stronger or weaker signals.

9.7 Worked Example 1: Dudley 844m dual track brick arch tunnel, 100mph

Dudley is a shorter 844 metre dual track brick lined tunnel. The wireless connectivity target is ≥100 Mbps directly to passenger devices, so the usable signal propagation range must be adjusted for additional train losses assumed up to 15 dB.

The tunnel fitment solution must make provision for cell handover periods of up to 5 seconds assuming a maximum line speed of 100 mph.

Table 32 works through the assessment of the scenario and some solution options.

Option selection process to work through Candidate Scenario		Relevance to option selection	Option selection data
1	**Tunnel for fitment** Dudley Tunnel 844m long	a) Length of tunnel sets coverage range.	**d = 844 m** (Tunnel length) [input]
	Brick-lined Dual track	b) Select signal propagation from lookup table cell: • Brick-lined tunnel • Dual track	**Tunnel Type = dual-track, brick**

		Go to step 2 to confirm connectivity and relevant carrier frequency to apply to range prediction.	
	Cell handover must work at line speeds up to 100 mph (allowing a handover window of 5 s)	Calculate minimum cell handover and impact on usable range.	**Cell handover distance ≥ 225 m** from Table 10 (Section 6.1) **Reduce signal propagation element usable range by 120 m**
2	**Select connectivity requirement**		
	a) Required minimum target data rate.	Basic requirement.	
	b) Direct connectivity from MNO trackside antenna to passenger device.	Reduce usable signal propagation range caused by additional train losses (shadowing, vehicle penetration and body losses) - **using the loss assumptions from Tables 11 and 12 for dual-track at all frequencies**	**15 dB additional train loss**
	c) Wireless technology generation	Iterate through several potential combinations of (c-e).	
	d) Allocated spectrum carrier frequency and signal bandwidth	Options listed in Table 8.	
	e) Special features	Options listed in Table 8.	
	Assessment of sub-options		
	2-1 Single signal band solution	**Carrier frequency must be > 5 GHz so would not work for direct connectivity.**	*Sub-option 2-1 rejected*
	2-2 4G/ 5G Cellular carrier aggregation by single or two MNOs combining: • 1,800 MHz 2 x 20 MHz (52 Mbps) • 2,600 MHz 2 x 20 MHz (52 Mbps) or • 3,800 MHz 1 x 40 MHz (93 Mbps)	**OK for data capacity.** User propagation range depends on ‘blueprint’ architecture and antenna siting so **go to Step 3.**	*Sub-option 2-2 still in play*

Table 32 - Worked example 1: Dudley Tunnel

	Option selection process to work through Candidate Scenario	Relevance to option selection	Option selection data
3	**Select ‘blueprint’ architecture fitment solution options:**	Identify potential options but propagation range will be important	
	3-1 S1 Near portal directional antenna	Compatible subject to signal range	*Sub-option 3-1 in play*
	3-2 S2.1 Portal directional antenna	Compatible subject to signal range	*Sub-option 3-2 in play*
	3-3 S2-2 Portal radiating cable	Compatible subject to signal rang **Go to step 4**	*Sub-option 3-3 in play*
4	**Calculate the usable signal range r of the ‘blueprint’ architecture elements**	For sub-option 2-2 so signal propagation ranges can now be looked up in Table 15 at 1,800 MHz/ 2,600 MHz/ 3,600 MHz. We need a minimum range of 0.5 x 850 + 120 m = 550 m	Additional train losses of 15dB (Table 11) reduce range to 18% of indirect connectivity range Reduce range by 120 m for cell handover
	3-1 S1 Near portal directional antenna	**Insufficient range - reject**	*Sub-option 3-1 in rejected*
	3-2 S2.1 Portal directional antenna	Range OK 1800 MHz and 3,600 MHz, not 2,600 MHz 1,800 MHz **r** = 700-120 = **580 m** 2,600 MHz **r** = 250-120 = 130 m	*Sub-option3-2 in play* **r > 550 m OK**

		3,600 MHz **r** = 800-120 = **680 m**	
	3-3 S2-2 Portal radiating cable	Range OK 1800 MHz and 2,600 MHz, not 3,600 MHz 1,800 MHz **r** = 1,100-120 = **980 m** 2,600 MHz **r** = 750-120 = **630 m** 3,600 MHz **r** = 450-120 = 330 m	*Sub-option3-3 in play* **r > 550 m OK**
5	**Calculate the relative cost of tunnel fitment (& Steps 6 and 7)**	Compare sub-options 3-2 and 3-3 for cost.	
	3-2 S2.1 Portal directional antenna	£160,000 selected on price	**Preferred option** **S2.1 portal directional antenna system operating with carrier aggregation at 1,800 MHz and 3,600MHz** **Relative cost £160,000**
	3-3 S2-2 Portal radiating cable	£850,000 rejected on price	

Table 32 (cont.) - Worked example 1: Dudley Tunnel

9.8 Worked Example 2: 4.9km Standedge (Old) Single Track brick-lined, 75mph

Standedge Old Tunnel is a long 4.9 kilometre single track brick-lined tunnel.

Two different wireless connectivity targets are considered assuming indirect connectivity, first a modest ≥ 50Mbps and then a more challenging ≥ 500Mbps for a busier railway. The tunnel fitment solution must make provision for cell handover periods of up to 5 seconds assuming maximum line speeds of 75 mph.

9.8.1 Required data rate ≥ 50 Mbps

Table 33 works through the assessment of the scenario and some solution options. The lowest cost solution is imperative given the low anticipated route usage.

Option selection process to work through Candidate Scenario		Relevance to option selection	Option selection data
1	**Tunnel for fitment** Standedge Old Tunnel 4,882m long	a) Length of tunnel sets coverage range	**d = 4,900 m** (Tunnel length) [input]
	Brick-lined single-track	b) Select signal propagation from lookup table cell: • Brick-lined tunnel • single-track **Go to step 2 to confirm connectivity and relevant carrier frequency to apply to range prediction**.	**Tunnel type = single-track, brick**
	Cell handover must work at line speeds up to 75mph (allowing a handover window of 5s)	Calculate minimum cell handover and impact on usable range	**Cell handover distance ≥ 170m** from Table 10 (Section 6.1) **Reduce signal propagation element usable range by 90 m**
2	**Select connectivity requirements**		
	a) Required minimum target data rate	Basic requirement	**≥ 50 MBps target data rate**
	b) Indirect connectivity to external train antenna and on-train gateway	Minimise infrastructure costs by maximising the usable signal propagation range of installed antennas	
	c) Wireless technology generation	**Simplest option is single carrier frequency 4G/ 5G**.	

Option selection process to work through Candidate Scenario		Relevance to option selection	Option selection data
	d) Allocated spectrum carrier frequency and signal bandwidth	Options listed in Table 8: **Any cellular frequency ≥1,800 MHz could provide ≥52 Mbps.**	
	e) Special features	None	
3	**Select 'blueprint' architecture fitment solution options:**	**Simplest option is important. The tunnel is long, but a pair of antennas may have sufficient signal propagation range.**	
	S2.1 Portal directional antenna	**Check usable range. Go to step 4.**	
4	**Calculate the usable signal range r of the 'blueprint' architecture elements**	Reduce range by 90 m for cell handover	
	S2.1 Portal directional antenna	Require usable range from Table 18 (and adjusted for cell handover) to be ≥ 5 x 4,900 ~2,500 m. OK at 1800 MHz and 2,600 MHz. Slightly lower range for 3,600 MHz 1,800 MHz **r** = 5,000-90 = **4,900 m** 2,600 MHz **r** = 5,000-90 = **4,900 m** 3,600 MHz **r** = 3,750-90 ~ **3,700 m**	**S2.1 solution at 1,800 MHz or 2,600 MHz OK**
5	**Calculate the relative cost of tunnel fitment (& Steps 6 and 7)**		
	S2.1 Portal directional antenna	£110,000 selected on price	**Preferred option** **S2.1 portal directional antenna system operating at 1,800 MHz or 2,600 MHz at a relative cost £110,000**
	S3.2 In-tunnel radiating cable solution	£1,400,000 more than ten times the relative cost of the S2.1 option. Rejected on cost grounds alone	

Table 33 - Worked example 2a: Standedge Old Tunnel, ≥50 Mbps

9.8.2 Required data rate ~500 Mbps

Table 34 works through the assessment of Standedge Old Tunnel with a much more demanding data rate of ~500 Mbps to the trainload of passengers.

Option selection process to work through Candidate Scenario		Relevance to option selection	Option selection data
1	**Tunnel for fitment** Standedge Old Tunnel 4,882 m long	a) Length of tunnel sets coverage range	**d = 4,900 m** (Tunnel length) [input]
Otherwise as for Table 33… until…			
2	**Wireless connectivity**		
	a) Required minimum target data rate	Basic requirement	**~500 Mbps target data rate**
	b) Indirect connectivity to external train antenna and on-train gateway	Minimise infrastructure costs by maximising the usable signal propagation range of installed antennas	
	c) Wireless technology generation	**Simplest option is mmWave.**	

Option selection process to work through Candidate Scenario	Relevance to option selection	Option selection data
d) Allocated spectrum carrier frequency and signal bandwidth. Two Options: (i) 2-1 26 GHz 1 x 200 MHz (450 Mbps) (ii) 2-2 60 GHz 1 x 2,160 MHz (600 Mbps)	Options listed in Table 8 **26 GHz or 60 GHz mmWave solution to provide at least 450 Mbps.** **Go to step 3**	
e) Special features	None.	
3 Select 'blueprint' architecture fitment solution options:	**The tunnel is long, and the range of high frequency integrated active antennas is too short other than an S3.1 in-tunnel active antenna system.**	
S3.1 Portal high frequency active antennas	**Check usable range. Go to step 4**	
4 Calculate the usable signal range r of the 'blueprint' architecture elements	Reduce range by 90 m for cell handover	
S3.1 Portal high frequency active antennas	Require usable range from Table 18 (and adjusted for cell handover) 26GHz has far better usable range 26 GHz **r** = 750 -90 = **640 m** 60 GHz **r** = 450-90 = **360 m** **Number of in-tunnel units** **n** is integer **n ≥ (d /2r) – 1** = 4,900/2/640 -1 **= 2.8 so n=3**	**S3.1 solution at 26 GHz OK** **n = 3 number of in-tunnel units**
5 Calculate the relative cost of tunnel Fitment		
S3.1 Portal high frequency active antennas.	£420,000	**Preferred option S3.1** Portal high frequency active antennas **with three in-tunnel units operating at 26 GHz at a relative cost of £420,000.**

Table 34 - Worked example 2b: Standedge Old Tunnel, ~500 Mbps

10 Conclusions

10.1 Signal propagation loss analysis and wireless connectivity options

The study has investigated radio frequency signal propagation between a trackside transceiver and a mobile transceiver on a train approaching, leaving, or travelling through a mainline railway tunnel in Great Britain.

Using basic signal propagation principles, available modelling tools, previous research, and radio frequency test measurements carried out at Dudley, Standedge (Old) and Copenhagen (East) tunnels, this study provides practical predictions of how signal propagation loss varies with distance for six typical tunnel types: whether single-track or dual-track and designed, constructed, and lined with brick, unlined rock, or reinforced concrete.

Significant elements of the model and underlying assumptions include the:

- **Target connectivity data rate**. This needs to be within the fundamental capacity of a given carrier frequency and signal bandwidth and sets the minimum local signal power level required throughout the tunnel.

- **Wireless connectivity concept**. Addressing whether direct or indirect connectivity using cellular or other carrier frequencies is preferred. For simplicity, whatever provides at least -105 dBm signal power throughout the tunnel.

- **Choice of propagation antennas** (related to propagation loss and RF power link budgets). There are three options, two are directional antennas, with passive antenna heads at cellular frequencies and integrated active antenna packages above 5 GHz, plus radiating cable at cellular frequencies.

  The usable range of each depends on RF power link analysis since the target minimum signal power in the tunnel depends on the transmitter power adjusted for antenna gains and various losses and the Maximum Allowed Path Loss (MAPL) caused by tunnel signal propagation loss. The usable propagation range of the antenna is the distance at which the signal propagation loss reaches the MAPL. Similar analysis has been completed for radiating cables using empirical data from manufacturers' data sheets.

- **Reference architecture design elements**. These are the individual elements that can deliver aspects of tunnel connectivity. Each element comprises an antenna sited at one of three possible locations: 'Near Portal', meaning 30 to 60 metres away from the tunnel portal and offset to the side of the track, 'At Portal' at the entrance to the tunnel, or 'In-tunnel' to provide coverage throughout longer tunnels. Each element is also configured to propagate in both directions along the track to support cell handovers along the line of route.

  The option selection tool lists usable signal range values in lookup tables for each architecture element for both direct and indirect connectivity, by tunnel type and carrier frequency. Options can be ruled out immediately if their range is too short, for example, 'Near Portal' directional antennas cannot provide direct connectivity to passenger devices passing through single track tunnels at any frequency.

- **Practical configurations**. The combination of design elements delivers a whole-of-tunnel solution, determined by the length of the tunnel and usable range of each element. Practical considerations may also immediately rule out certain approaches. For example, a certain amount of physical space is required to mount the active electronics and supply the power and optical fibre connections. These aspects need to be compliant with Network Rail standards associated with product approvals, train clearances, lightning, and surge protection.

- **Relative capital and operational costs.** The relative fitment costs of each tunnel solution may be calculated based on the representative unit costs of each architecture design element, adjusted for the variable costs associated with the length of the tunnel bore(s). It is assumed that annual operating and maintenance costs are 12% of the relative fitment cost.

Worked examples have been developed to show how the guidelines can be used to determine potential tunnel fitment options and the options to consider. The cost models presented in this report are indicative and budgetary and are provided to show the relative costs of different tunnel designs, not for planning purposes. Detailed tunnel surveys should always be undertaken prior to any works.

It is beyond the scope of this study to provide costs associated with the mobile network operators' active equipment and their overheads, noting that these would in many cases be similar regardless of the tunnel fitment approach. option. Other excluded costs include project, contract and engineering management, safety and quality assurance, access planning, installation, and commissioning.

10.2 Causes of tunnel signal propagation loss

It has proved difficult to model real signal propagation within GB rail tunnels with any precision and especially not the various types of signal fading caused by constructive and destructive interference of wavefronts. Commercial models tend to concentrate on adjustments to free space path loss models where loss varies inversely with the square of distance. Whilst there are many examples in the literature reporting attempts to apply Maxwell's equations to model aspects of tunnel propagation these are not consistent with this study's RF test measurement results.

These real-world findings forced a reconsideration of many of the initial assumptions, including the effectiveness of in-house and proprietary modelling tools. Instead, a fundamental review of signal propagation principles was conducted to seek plausible, if not definitive, explanations for the RF signal propagation loss measurements using directional antennas at three tunnels at Dudley, Standedge (Old), and Copenhagen (Eastern Bore). There are many mechanisms involved, all of which vary differently with signal wavelength and distance into the tunnel:

- **In some cases, there may be no electromagnetic interaction between signal and tunnel surfaces that can be detected at the receiver**. This is evidenced by free-space path loss behaviour where signal power decays inversely with the square of distance. This occurs at higher frequencies (20-60 GHz) when the tunnel profile is relatively large (of the order of 100-1000 wavelengths). Conversely, free space transmitter antennas are also more efficient at lower frequencies, explaining why initial signal loss closer to the antenna is less at lower frequencies.

- **The transition to coupling of the signal with the tunnel as a waveguide occurs first at low frequencies because of the faster growth in diameter of the Fresnel Zones**. This mechanism is also consistent with the 'breakpoint' identified by several theoretical international studies.

- **Rail tunnels behave as very "lossy" dielectric waveguides.** An electromagnetic waveguide will only propagate energy at a finite number of propagation modes. The highest order modes are like rays directed almost at right angles and directly towards tunnel surfaces, while the lowest modes follow the alignment of the tunnel, skimming the tunnel surface. Rail tunnels have high refractive index surfaces, so the higher modes tend to be lost by refraction (bending) and transmission into the tunnel surfaces. A greater proportion of lower mode rays are partially reflected but the process is always lossy. The total signal will always suffer continuous decay as it passes along the tunnel because of this constant leakage. Signal propagation loss is initially higher as the higher order modes attenuate rapidly with distance. Deeper into the tunnel, fewer modes persist, and each will continue to decay exponentially (appearing as a straight line on a logarithmic signal propagation loss (dB) versus linear distance in metres chart). Higher carrier frequency mode waves tend to propagate better than lower frequencies. Larger profile tunnels support propagation better than narrow tunnels because of reduced interaction with tunnel surfaces and smaller train shadowing effects.

- **The receiver antenna will be sensitive to changes in alignment or position across the face of the tunnel.** The antenna can only detect those modes that couple into it and so cannot detect all the energy travelling along the tunnel. This effect may explain why it is possible to detect a sudden anomalous reduction in signal propagation loss with range.

- **Signal attenuation is also affected by variations in the alignment, surface quality and electromagnetic properties of the tunnel surfaces.** Losses are higher at higher frequencies because lower frequencies are less affected by fine variations in tunnel surface geometry of less than a tenth of a wavelength. The roughness tends to convert lower propagation modes into lossier higher modes.

- **The received signal is subject to multiple signal fading effects impossible to predict by deterministic modelling**. The erratic variation in amplitude of propagating waves with distance was first explained by Huygens' principle of diffraction, as the result of constructive and destructive mixing of different wavefronts.

There are many mechanisms that cause RF waves to scatter and diffract or create standing waves from forward and backwards waves propagating within waveguides. The effects are strong but impossible to predict deterministically because they are so sensitive to small variations in local geometry and material properties. Fading will always impair wireless connectivity, particularly on moving trains, but this can be mitigated by operating conditions and system design, with modulation and coding technologies and Multiple Input Multiple Output (MIMO) antenna configurations reducing the effect.

- **Tunnel surfaces will also affect signal polarisation because RF signal reflectance varies with polarisation (known as the Brewster effect)**. This may reduce the MIMO benefits of a pair of cross-polarised directional antennas, especially through longer tunnels.

- **Additional train losses caused by Vehicle Propagation Loss, User and Crowding Body Loss and barriers presented to tunnel signal propagation by the train itself (train shadowing) reduce the usable signal propagation range for direct connectivity to passenger devices.** A relatively modest additional train loss of 15 dB reduces the effective range by 80% compared with indirect connectivity methods, and 97% if these losses are 30 dB.

The various signal propagation loss characteristics observed may be explained as a combination of effects.

Lower carrier frequency signals suffer a lower initial loss but start to couple from transmitter to tunnel waveguide propagation modes sooner because their Fresnel zones grow in diameter faster than at higher frequencies.

Lower carrier wave frequency propagation modes attenuate also faster than higher frequencies, especially along smooth tunnels with regular geometry (such as built from reinforced concrete segments). However, higher frequency modes are also more susceptible to scattering losses within tunnels with rough or uneven surfaces.

The receiver antenna will detect local signal fading effects and abrupt changes (even reductions) in loss because of changes in tunnel geometry, electromagnetic properties, or humidity/ surface water, or by misalignment of the receiver. These effects are shown graphically in Figure 26.

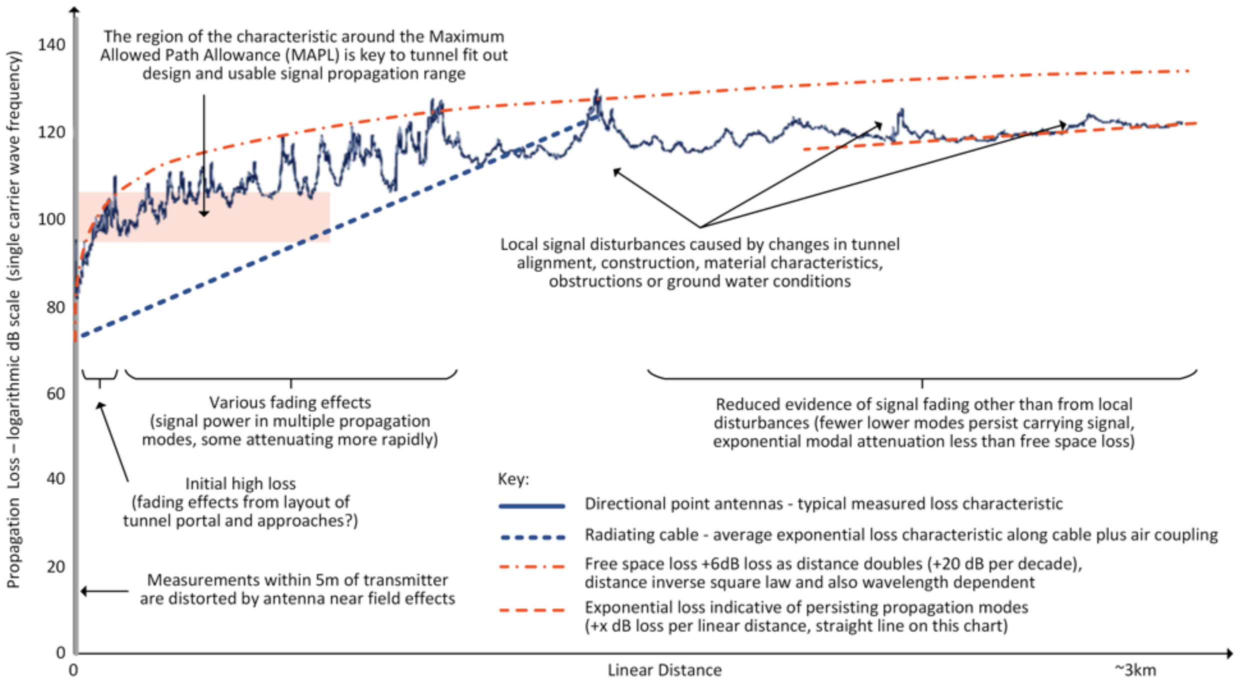


Figure 26 - Typical tunnel signal propagation loss characteristics

From an engineering perspective, the critical region of the characteristic is solely that region of the curve that is close to the Maximum Allowed Propagation Loss within which the RF power link budget of an antenna system will work.

10.3 Tunnel fitment implications

This study has confirmed the results of a parallel study on rail carriage signal attenuation [6] that railways face unique wireless connectivity issues because both rail tunnels and carriage construction introduce a far wider range of signal attenuation compared with domestic dwellings and cars (7-10 dB).

As higher data capacity demands will drive the need for higher frequency spectrum, such signal attenuation issues will only get worse since higher frequencies tend to be attenuated more passing through materials such as steel and aluminium. Therefore, this study has considered not only direct connectivity between mobile network operators' base stations and passenger devices, but also indirect connectivity using an external train antenna and on-train gateways redistributing the external signals where the carriage attenuation does not need to be considered.

Please note the following findings are derived from the option selection process and associated lookup tables. Business sponsors may wish to investigate other options. All costs quoted are indicative and relative, since they count only the fitment costs needed to compare options. They also exclude mobile operators' own network costs.

10.3.1 Direct connectivity to passenger devices

Some fitment solutions can be ruled out because they can not deliver sufficient range, taking tunnel propagation and additional train losses into account. These include:

- 'Near Portal' directional antennas for any tunnel type.
- 'At Portal' directional antennas for most single-track tunnels, except where the lowest carrier frequencies (800 MHz) are used.
- Any solution using frequencies above 4 GHz.

The analysis assumes only modest additional train losses of 15 dB, noting too that 'At portal' directional antennas solutions would be ruled out for any tunnel if the additional train losses are closer to 30 dB.

The relative appeal and costs of the remaining tunnel fitment options varies by application. For example:

- £160,000 would provide greater than 100 Mbps capacity direct to passengers throughout the 844-metre dual-track brick-lined Dudley tunnel with an 'At Portal' directional antenna solution using aggregated cellular carrier frequencies. This is c.20% of the cost of an alternate 'At Portal' radiating cable solution (£850,000).
- There is no feasible solution for single-track tunnels, as directional antennas will not work, and radiating cable alternatives would be too expensive assuming ~£1,000,000 per km for shorter tunnels, falling to approximately £250,000 per kilometre for a longer 5 km tunnel requiring in-tunnel reinforcement.

Whilst the different tunnel construction materials make some difference to the variable costs (given additional fixing requirements for example), they do not change the preferred solution. With brick constructed tunnels as a baseline, unlined rock is assumed to have slightly lower usable ranges, while smooth, regular, reinforced concrete tunnels have somewhat longer ranges.

10.3.2 Indirect connectivity

Indirect connectivity offers a potentially far wider range of tunnel fitment options at more competitive infrastructure costs. Higher frequency solutions exploiting integrated active antennas are even cheaper, though do not reflect the associated additional train fleet, route-fitment, or connection costs.

Indirect connectivity can be achieved by a range of tunnel fitment solutions that can be optimized for the requirement, for example:

- £110,000 would fit the 4.9km single track brick lined Standedge Old Tunnel using an 'At Portal' directional antenna solution offering greater than 50 Mbps to the train and hence passengers. A radiating cable solution would cost more than ten times more (£1,400,000) albeit would delivery a better data rate. A 'Near Portal' solution would be approximately £160,000 as it includes the mast and concrete bases.

- £420,000 would fit a busier equivalent of Standedge Old Tunnel providing greater than 500 Mbps, assuming there was space for three 'In Tunnel' integrated 26 GHz active antenna repeaters plus 'At Portal' active antennas at both ends of the tunnel. This is still £1,000,000 cheaper than radiating cable. By comparison an 'In Tunnel' cellular directional antenna system would cost 20% more (£550,000) but only provide approximately 100 Mbps even with carrier aggregation.

10.3.3 Whole life costs

In practice, both direct and indirect connectivity solutions cannot be compared without a consideration of the overall combined train fleet, route and tunnel fitment whole life costs. Noting too that the deployment of mmWave technologies typically requires a contiguous line of route to be installed to deliver a constant service offer for passengers.

10.4 Wider implications

This study concludes that the technical challenge of providing wireless connectivity that works well for most passengers wanting to use their mobile devices is more difficult and costly than may have been previously assumed.

Although fitment solutions for direct connectivity to passenger devices can be devised for all tunnels, many may be expensive and not always perform well. Railways differ from cars and domestic dwellings because of the wide range of signal losses that can occur, and any technical solution introduces complex commercial and technical interfaces between the mobile network operators, alternate infrastructure and service providers, rail infrastructure and the train. In particular:

- The complex stakeholder environment means funding improved tunnel coverage (and rail corridor connectivity generally) is often a challenge, given that benefits accrue to different parties.

- To meet the ever-increasing demand for data and data speeds higher carrier frequencies will be needed, needing more trackside infrastructure and indirect connectivity to avoid train carriage attenuation affects. In turn this will require multi-carrier or technology agnostic on-train gateways capable of re-distributing these signals.

- JOTS for Rail collaboration offers opportunities for economies of scale reducing the trackside and tunnel infrastructure required, especially if all train-originating and terminating mobile operator traffic can be aggregated to and from the MNOs core networks, rather than trackside as today.

Realising improved wireless connectivity will require that these wider challenges are addressed.

*   *   *

Glossary

Abbreviation	Definition
2G	Second generation mobile telephone system (or GSM)
3G	Third generation of mobile telephone system (or UMTS)
3GPP	Third Generation Partnership Project, a global initiative for mobile telecommunications standards
4G	Fourth generation of mobile telephone system [also known as Long Term Evolution LTE]
5G	Fifth generation of mobile telephone system (or NR)
α	[Alpha] Greek letter used to denote an angle
ACM	Adaptive Coding and Modulation
AGL	Above Ground Level
AoA	Angle of Arrival
ATPC	Automatic Transmit Power Control
BBU	Base Band Unit
BCIMO	Black Country Innovative Manufacturing Organisation, operators of Dudley tunnel.
BEREC	Body of European Regulators for Electronic Communications
BTS	Base Transceiver Stations.
CA	Carrier Aggregation (available since 3G+)
CPE	Customer Premises Equipment
CPiCH	Common Pilot Channel: This channel is used in UMTS to enable channel estimation
CTIA	Cellular Telephone Industries Association
CW	Continuous Wave
DAS	Distributed Antenna System
dBm	decibel-referenced to 1 milliWatt, a logarithmic measure of signal power where 1 mW = 0 dBm, and -10dB represents a reduction in power by a factor of 10. For example: 0.1mW = 1mW/10 = 0dBm – 10dB = -10dBm
DCMS	Department for Digital, Culture, Media & Sport
DfT	Department for Transport
DL	Down Link
D-OBR	Digital On-Board Repeater
DSS	Dynamic Spectrum Sharing
DTN	Data Transmission Network
EDOR	ETCS Data Only Radio
EIRENE	[GSM-R Voice] European Integrated Railways Radio Enhanced Network
EiRP	Effective isotropic Radiated Power
ELR	Engineer’s Line Reference
eMLPP	[GSM-R Voice] enhanced Multi-Level Precedence and Pre-emption
EMR	East Midlands Railway
EN	Euronorm
E	[Epsilon] Greek letter used to denote electrical permittivity
ERA	European Railway Agency (European Union Agency for Railways)
ERTMS	European Rail Traffic Management System
ESN	Emergency Service Network
ETCS	European Train Control System as defined by the Technical Specifications for Interoperability for Command, Control and Signalling (CCS). ETCS delivers Automatic Train Protection
EU	European Union

Abbreviation	Definition
EuCap	European Conference on Antennas and Propagation
FDD	Frequency-Division Duplex
FRMCS	Future Railway Mobile Communications System, an initiative set up in 2012 UIC to develop future user requirements for a successor to GSM-R
FSPL	Free Space Path Loss
FTN	Fixed Telecommunications Network
FWA	Fixed Wireless Access
GB	Great Britain
Gbps	Giga bits per second (1,000,000,000 bits of data per second) or 1,000 Mbps
GHz	GigaHertz, 1GHz = 1,000 MHz
GPRS	General Packet Radio Service
GRIP	[Network Rail] Governance for Railway Investment Projects
GSCM	Geometry-based Stochastic Channel Model
GSMA	Groupe Speciale Mobile Association
GSM-R	Global System for Mobile [Communications] (Railway)
GWR	Great Western Railway
HMI	Human Machine Interface
HSPA+	High Speed Packet Access plus
HSR	High-Speed Railway
HST	High Speed Train
IP	Internet Protocol
JOTS Rail	Joint Operator Technical Specification for Rail
Λ	[Lambda] Greek letter used to denote wavelength.
LOC & PAS TSI	European Union Technical Specification for Interoperability concerning locomotive and passenger rolling stock
LTE	Long Term Evolution [4G]
MAPL	Maximum Allowed Path Loss
Mbps	Megabits per second (1,000,000 bits of data per second)
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output [antennas]
mmWave	Millimetre Waves. Extremely high frequency electromagnetic radiation with wavelengths of the order of millimetres (e.g. wavelength= 5mm @ 60GHz, 11.5mm@ 26GHz). Also known as V-band.
MNO	Mobile Network Operator
μ	[Mu] Greek letter used to denote magnetic permeability.
MSC	Mobile Switching Centre
NA	Not Applicable
NF	Noise Figure (noise created by mobile phone device)
NIC	National Infrastructure Commission
NPRB	Non-Ionizing Radiation Protection Board
NR	Network Rail, (New Radio in the context of 5G)
NTR	[National] Notified Technical Rule
OCS	Overhead Catenary System
OFDM	Orthogonal frequency-division multiplexing
OH	Control Overheads
OLE	Overhead Line Equipment

Abbreviation	Definition
OMU	Optical Multiplexer Unit
OTA	Over the Air
Pax	Passengers
Π	[Pi] Greek letter used to represent the irrational number 3.1416…
PRB	Physical Resource Block
PTS	Personal Track Safety
RBE	Risk-based Evaluation
RIDC	[NR] Rail Innovation & Development Centres providing train test tracks at: Melton Mowbray, Leicestershire (high speed, electrified) and Tuxford, Nottinghamshire (not electrified)
RAN	Radio Access Network
REC	[GSM-R Voice] Railway Emergency Call
RF	Radio Frequency
RGS	GB Railway Group Standard
RIS	GB Railway Industry Standard
ROSCO	Rolling Stock Company
RRU	Remote Radio Unit
RSCP	Received Signal Code Power (3G UMTS)
RSRP	Reference Signal Received Power (4G LTE and 5G NR)
RSRQ	Reference Signal Received Quality
RSSB	Rail Safety & Standards Board
RSSI	Received Signal Strength Indicator
RxLev	Received power Level (for GSM)
Rx	Receive
SCADA	Supervisory Control and Data Acquisition
SCS	Sub-Carrier Spacing
SE	Spectral Efficiency
Σ	[Sigma] Greek letter used to denote electrical conductivity.
SINR	Signal-to-Noise-and-Interference-Ratio
SISO	Single Input Single Output [antenna]
SOTA	State-Of-The-Art
SWR	South Western Railway
TDD	Time-Division Duplex
TfL	Transport for London
θ	Theta - Greek letter used to denote an angle
TF	Transport Focus
TOC	Train Operating Company
TRP	Total Radiated Power
TIS	Total Isotropic Sensitivity
TX	Transmit
UE	User Equipment
UIC	Union Internationale des Chemins de Fer (International Union of Railways)
UL	Up Link, a commercial branch of Underwriters Laboratories that undertakes mobile handset tests
UMTS	Universal Mobile Telecommunications System [3G]
VPL	Vehicle Penetration Loss
W-CDMA	Wideband Code Division Multiple Access

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Appendices

Appendix 1
Tunnel Assumptions

App1.1 Tunnel Categories

DfT and Network Rail supplied three data sets (Table 35) that identified a total of 712 tunnels. This was reduced to 634 operational tunnels, although 12 of these are unsignalled. The others were either duplicates (61), non-operational (11) or no longer retain their original cross section (6 removed, part filled or unknown).

Item	Spreadsheet	Data provided
1	Tunnel bore export: 'GeoRINM – DataSourceTunnelBore – Export_29_01_2020 (HA).xlsx'	Primary and secondary material, construction form, construction details, length
2	Cross sections and route descriptions: '200808 GB Network Rail Summary Cross Sections and ROUTE descriptions.xlsx'	Eastings and Northings (from which horizontal curvature is be derived).
3	GSM-R tunnel dataset: '200310 GN GSMR and Tunnel Dataset.xlsm'	Number of tunnel bores (from which number of tracks is derived).

Table 335 - Tunnel datasets supplied by DfT and Network Rail

The study team has made several assumptions to work around the limitations of the datasets (Table 36).

Item	Details	
1	Length less than 10m:	Bridge, not tunnel, and excluded from this study.
2	Length between 10m and 50m:	Very short tunnel assumed not to require technical in-fill solution.
3	Tunnels between 50m and 260m:	Short tunnel as the limit for an end-fed technical in-fill solution, based on the GSM-R dataset.
4	Brick and (cut) stone have similar properties.	
5	Bare rock and sprayed concrete have similar properties, as do tunnels with bare rock abutments capped with brick arches.	
6	Default construction type unless explicitly described otherwise: • Type A 'Brick arches with iron or steel beams' are jack arches • Type B 'Brick or rock tunnels' are arched • Type C Segmental 'concrete' lining is circular	
7	Categorised as 'mixed' construction type if comprises: • More than two different construction materials, or • More than one form. Portal materials do not count, for example, stone portal with brick arch tunnel. Avalanche shelters are ignored.	
8	Expected portal construction by tunnel type to be the same as the main tunnel, although: • Cast iron tunnels have concrete portals, and • Rock tunnels may have a concrete portal if the natural rock has needed to be stabilised.	
9	Tunnels described as single bore are deemed to service two tracks while multi-bore tunnels comprise multiple single-track bores.	

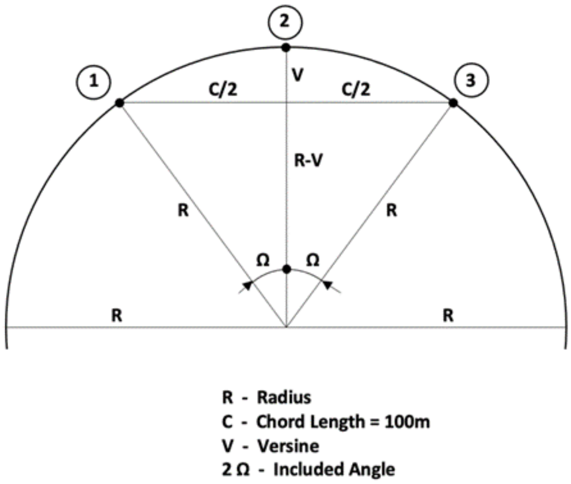
Table 346 - Assumptions: Tunnel datasets

App1.2 Tunnel Curvature metrics

Track curvature was calculated from the eastings and northings, given at 50 metre intervals provided on the cross sections and route descriptions spreadsheet. This meant that tunnels less than 100 metre in length could not be classified for curvature.

Tunnel curvature was calculated using three cross section points and classified by the versine associated with a 100-metre chord as considered easiest to visualise the curvature.

The equivalent radius (**R**) and included angle (**2Ω**) for the calculation of versine are shown in Figure 27 below.



If **v<<R** then **v ~ c^2/8R** [55]

Figure 27 - Relationship between radius of curvature, versine and included angle

Appendix 2
Connectivity Configuration Assumptions

App2.1 Connectivity Configuration

Technology	2G/GSM	3G/UMTS	4G/LTE	5G/NR	wifi
Voice	✓	✓	✓	✓	✓
Data	×	×	✓	✓	✓

Table 357 - Relevance of mobile technology to voice and data services

Technology	Duplex Method	MIMO	Frequency Band (MHz)	Test Frequency (MHz)	Channel Bandwidth (MHz)
2G GSM	FDD	Voice only	900	890	0.2
2G GSM	FDD	Voice only	1,800	1,801	0.2
3G UMTS	FDD	Voice only	900	890	5
3G UMTS	FDD	Voice only	1,800	1,801	5
4G LTE	FDD	2T2R	900	890	5, 10 or 20
4G LTE	FDD	2T2R	1,800	1,801	5, 10 or 20
4G LTE	FDD	2T2R	2,600	2,395	10, 20 or 40
5G NR	FDD	2T2R	700	703	5 or 10
5G NR	TDD (80% DL)	2T2R	3,400	5,510	20 or 40
Wifi	FDD	2T2R	700	703	5 or 10
Wifi	TDD (80% DL)	2T2R	3,400	5,510	20 or 40

Table 368 - Technology, frequency bands, and bandwidth

Parameter	Value
Subcarrier Spacing (SCS)	15 KHz
$Load_{Cell}$	85%
Control Overhead (OH)	22% (for 4G)/ 16% (for 5G)
Max. Modulation (256QAM)	7.4063 bits / Resource Element (RE)
Interference Margin	3 dB
Receiver Antenna Gain (GRx)	0 dB
Noise Figure	10 dB
Noise Floor	-174 dBm (referenced to 1Hz band)

Table 379 - Signal to interference plus noise ratio modelling parameters (4G/ 5G)

Bandwidth (MHz)	Resource Blocks (4G LTE)	Resource Blocks (5G NR)
5	25	25
10	50	52
15	75	79
20	100	106
25	-	133
30	-	160
40	-	216
50	-	270

Table 40 - Resource Blocks available for use (4G/ 5G)

Technology	High or Good	Medium or Sufficient	Low or Intermittent	No Service
2G GSM	At least -81 dBm	-81 to -93 dBm	-93 to -110 dBm	Less than -110 dBm
3G UMTS	At least -100 dBm	-100 to -103 dBm	-103 to -120 dBm	Less than -120 dBm
4G LTE	At least -105 dBm	-105 to -116 dBm	-116 to -121 dBm	Less than -121 dBm

Source: Ofcom 2019 [56, 57]

Notes:

a) *Signal power metrics differ by technology: RxLev (2G), RSCP CPI (3G) and RSRP (4G)*
b) *Linkage to voice quality of service expectations:*
   Good — *More than 95% probability of a successful voice call*
   Medium — *70-95% probability of a successful voice call*
   Low — *50-70% probability of a successful voice call*
   No service — *Worse than 50% probability of a successful voice call*

Table 41 - Quality of Service Indicators based on modelled signal power

App2.2 RF Power Link analysis configuration assumptions – directional antennas

Configuration by carrier band	800 MHz	1,800 MHz	2,600 MHz	3,600 MHz	5,500 MHz	26,000 MHz	67,000 MHz
Technology							
Generation	4G	4G	4G	5G	Wifi	5G	mmWave
Signal Bandwidth (MHz)	10	20	20	40	80	200	2,160
Duplex	FDD	FDD	FDD	TDD	TDD	TDD	TDD
Direction	DL	DL	DL	DL	DL	DL	DL
Direction Ratio	100 %	100 %	100 %	75 %	75 %	75 %	50 %
SCS (kHz)	15	15	15	15	78.125	60	-
Resource blocks	50	100	100	216	1024	264	-
Cell Loading	85 %	85 %	85 %	85 %	100 %	85 %	-
Overhead	22 %	22 %	22 %	14 %	9 %	14 %	-
Transmitter							
Power per antenna (dBm, W)	43 (20W)	43 (20W)	43 (20W)	25 (0.3W)	-	34 (2.5W)	-
Tx RSRP (dBm)	15.2	12.2	12.2	-9.1	-	-1.0	-
Tx RSRP relative to total power (dB, %)	-36.8 (0.021 %)	-30.8 (0.083 %)	-30.8 (0.083 %)	-34.1 (0.039 %)	-	-35 (0.032 %)	-
EIRP, all antennas (dBm)	-	-	-	-	30	-	40
No of Antennas	2	2	2	4	2	512	16
MIMO Rank	2	2	2	2	2	2	1
Antenna Gain (dB)	10.1	11.0	11.0	16.5	19.0	4.5	12
Tx CCC Losses (dB)	1	1	1	1	2.0	0.5	0.5
Antenna Height (m)	5.5 m	5.5 m	5.5 m	5.5 m	5.5 m	5.5 m	5.5 m
Receiver							
No of Antennas	2	2	2	4	2	32	16
Antenna Gain (dB)	5.0	6.0	7.5	6.5	8.0	4.5	12.0
Rx CCC Losses (dB)	1.0	1.0	1.0	1.0	2.0	0.5	0.5
Antenna Height (m)	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Body Loss (dB)	0	0	0	0	0	0	-
Doppler effect (dB)	3	3	3	3	3	3	-
Penetration Loss (dB)	0	0	0	0	0	0	0
Interference Margin (dB)	3	3	3	3	3	3	-
Link							
Cell-edge confidence	95 %	95 %	95 %	95 %	95 %	95 %	95 %
Propagation model	PL	PL	PL	PL	PL	PL	PL
Target RSPR/Rx Level (dBm)	-105	-105	-105	-105	-90	-105	-65
Maximum Allowed Path Loss (dB)	**120.8**	**119.7**	**121.2**	**131.9**	**97.4**	**118.0**	**125.5**

Table 382 - Configuration data for directional antenna systems (Source Real Wireless)

App2.3 RF Power link analysis configuration assumptions – radiating cables

Configuration by carrier band	**800 MHz**	**1,800 MHz**	**2,600 MHz**	**3,600 MHz**
Technology				
Generation	4G	4G	4G	5G
Allocated Signal Bandwidth (MHz)	10	20	20	40
Duplex	FDD	FDD	FDD	TDD
Direction	DL	DL	DL	DL
Direction Ratio	100 %	100 %	100 %	75 %
SCS (kHz)	15	15	15	15
Resource blocks	50	100	100	216
Cell Loading	85 %	85 %	85 %	85 %
Overhead	22 %	22 %	22 %	14 %
Transmitter				
Remote Unit (RU) Power (dBm, W)	43 (20W)	43 (20W)	43 (20W)	43 (20W)
Tx RSRP (dBm)	15.2	12.2	12.2	8.9
Tx RSRP relative to total power (dB, %)	-27.8 (0.17 %)	-30.8 (0.083%)	-30.8 (0.083%)	-34.1 (0.039%)
Far train extra loss (dB)	-	-	-	-
Tx CCC Losses (dB)	8	8	8	8
Longitudinal cable loss (dB/km)	19.0	33.2	51.1	79.0
Receiver				
No of Antennas	1	1	1	1
Antenna Gain (dB)	5	6	7.5	6.5
Rx CCC Losses (dB)	1	1	1	1
Antenna Height (m)	4.5	4.5	4.5	4.5
Body Loss	-	-	-	-
Doppler effect (dB)	3	3	3	3
Penetration Loss (dB)	-	-	-	-
Interference Margin (dB)	3	3	3	3
Noise Figure (dB)	10	10	10	10
Link				
Cell-edge confidence	95 %	95 %	95 %	95 %
Coupling loss @2m	74 dB	69 dB	69 dB	67 dB
RSRP target	**-105.0 dBm**	**-105.0 dBm**	**-105.0 dBm**	**-105.0 dBm**

Table 393 - Configuration data for radiating cable system (Source Real Wireless)

Appendix 3
Signal Propagation Principles – Supplementary Information

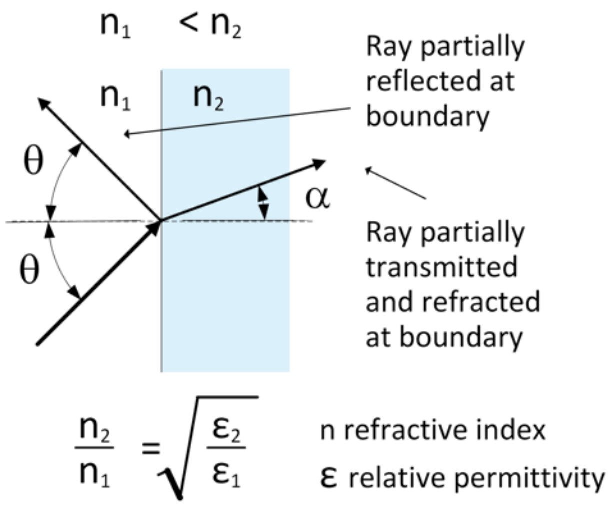
This Appendix contains supplementary information in support of Section 5 RF signal propagation within railway tunnels:

- Appendix 3.1 RF wireless propagation as rays.
- Appendix 3.2 Huygens' principle - radiation by constantly re-diffracted wavelets.
- Appendix 3.3 Line of sight propagation in free space (far field) – Friis transmission formula, how it varies with frequency/ wavelength and how additional losses degrade usable range.
- Appendix 3.4 Fresnel Zones - impact of obstructions on Huygens' principle of diffraction.
- Appendix 3.5 Impact of polarisation at boundary of two dielectric media.
- Appendix 3.6 Waveguides and their propagation modes.
- Appendix 3.7 Impact of random variations in geometry and material properties.
- Appendix 3.8 Antennas as waveguide coupling components.

App3.1 RF wireless propagation as rays

This idea assumes energy propagates and interacts with optical media and devices as rays. Rays are reflected or blocked by metal planes but bent or reflected at boundaries between transparent media of different refractive index.

The example illustrated (Figure 28) shows the ray travelling from a lower refractive medium into a medium with a higher refractive index (as encountered within a rail tunnel).



Snell's law suggests ***sin a/ sin q = n₁/n₂***.
Note*: if the ray had arrived from the optically denser medium ($n_1>n_2$) total internal reflection would occur at angles beyond the critical angle q_c > arcsin(n_1/n_2) q_c = 19.5° - 30° for dry rock/ brick (compared with 48.6° for water)*

Figure 28 - Reflection and refraction at boundary between different optical media

Maxwell's equations make clear that polarisation of electromagnetic waves (Appendix 3.5) affects reflectance at a boundary and the link between refraction and the electrical permittivity of dielectrics (electrical insulators). At a scale closer to the wavelength of the radiation, diffraction effects must be considered (Appendix 3.2).

Relevance to tunnel propagation:

- Tunnel lining ε ~5-10 so refractive index ~2-3.5 and can be higher [58, 59, 60].
- Only some RF radiation is reflected by the tunnel walls. Other energy is lost partial transmittance and refraction into the tunnel walls and partially reflected.
- Wavelength of RF radiation for wireless connectivity at frequencies 60 GHz down to 700 MHz is in the range 5-450 mm so diffraction of tunnel surface variations must also be considered.

- In the absence of other more dominant effects, the amount of light reflected along the tunnel will depend on the surface area of the tunnel that also depends on the perimeter of its cross-sectional profile

App3.2 Huygens' principle - radiation by constantly re-diffracted wavelets

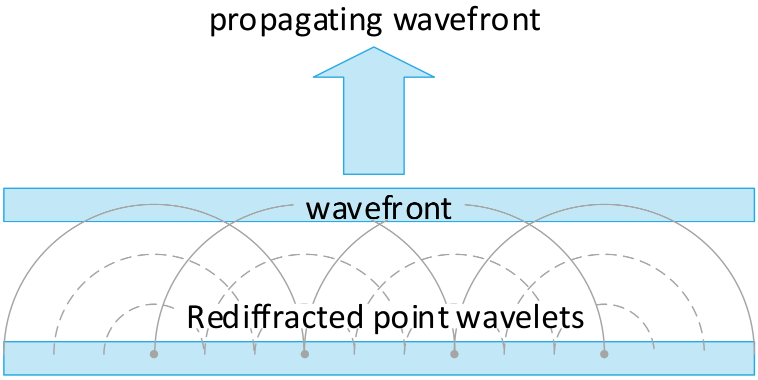


Figure 29 - Wavefront advances by re-diffraction of wavelets

Huygens postulated that radiation travels as wave fronts constantly re-diffracting (Figure 29). Each wavefront comprises individual point wavelet generators. This idea supports the observation of constructive and destructive interference between waves and diffraction at sharp edges, slits, and gratings at a scale like the wavelength of the radiation. It remains a powerful idea and Maxwell's equations supports many of its findings.

Relevance to rail tunnels:

- One explanation for multi-path fading by constructive and destructive interference of propagated, reflected, or diffracted waves.

- Diffraction must be considered at tunnel walls if the wavelength is like the dimension of surface variations, although not affected by variations less than ~λ/10 in size [10].

App3.3 Line of sight propagation in free space (far field) – Friis transmission formula

Friis' formula provides a useful indication of maximum signal power density (Wm^{-2}) at a distance **d** from a transmitter radiating evenly in free space to the surface of a sphere of radius **d** (Figure 30). The signal power decays proportional to $\mathbf{1/d^2}$ (inverse square of distance).

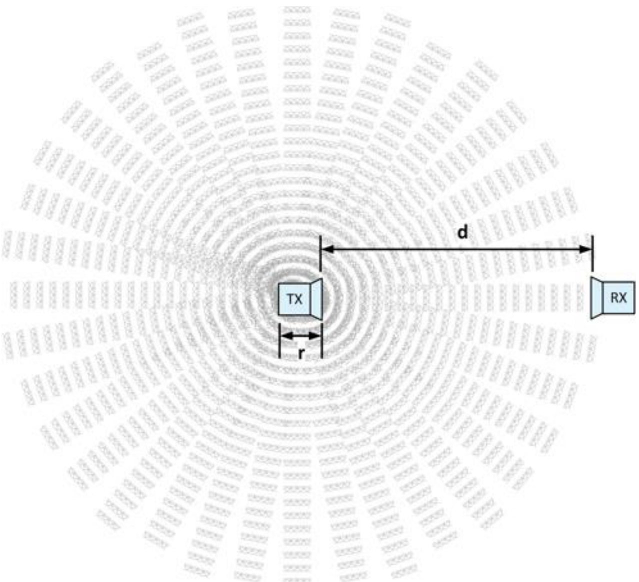


Figure 30 - Signal Propagation in free space

The actual signal power distribution is more complex and dependent on the design of the antenna. The Friis formula introduces gain factors (**G**) to consider actual transmit (Tx) and receiver (Rx) antenna directionality and its dependence on the wavelength of the radiation. The free space path loss (FSPL) represents the loss component independent of antenna effects and gains.

> ***Equivalent Isotropically Radiated Power (EIRP)*** is the power that comes out of an antenna in its main direction. The EIRP is the product of transmitter power of a radio transmitter and the antenna gain. The antenna gain is defined as the radiated power in each direction compared to the radiated power of an isotropic antenna connected to the same radio transmitter. An isotropic antenna is a theoretical antenna that radiates equally in all directions. Normally the EIRP is quoted in dBi, or decibels over isotropic and the higher the EIRP, the greater the range.

The Loss ratio between transmitter and receiver (Friis transmission formula):

Loss ratio = Power received / Power transmitted = $\mathbf{G_{tx}} \times \mathbf{G_{rx}} \times (\boldsymbol{\lambda/4\pi d})^2$ .... [Eq.A3-1]

The logarithmic form in dB (and showing dimensions):

Overall Loss (dB) = $\mathbf{G_{tx} + G_{rx} + (\lambda^2(\mathrm{m}^2)/16\pi^2) - 20\log(d(\mathrm{m}^{-1}))}$ .... [Eq.A3-2]

Free Space Path Loss (dB) = $\mathbf{(\lambda^2\,(\mathrm{m}^2)\,/16\pi^2) - 20\log(d(\mathrm{m}^{-1}))}$ .... [Eq.A3-3]

App3.3.1 Variation with carrier frequency and wavelength

Table 44 shows the impact of wavelength on free space loss by tabulating values of $\mathbf{\lambda^2/16\pi^2}$ when the **20 log (d**(m^{-1})**)** component is zero at **d = 1 metre**.

Carrier Frequency (MHz)	**Wavelength λ (millimetres)**	**Free Space Path Loss** when d = 1m = $\lambda^2/16\pi^2$ (dB)
800	375	-31
1,800	167	-38
2,600	115	-41
3,800	79	-44
5,500	55	-47
26,000	11.5	-61
60,000	5	-68

Table 404 - Free Space Path Loss varies with square of wavelength

Free space path loss predicts a loss of 6 dB per octave (20 dB per decade) by distance at a given wavelength.

The shape of the characteristic (for example see the dotted lines in Figures 41 and 44 of Appendix 4.3) does not change with wavelength but Table 44 highlights that the free space path loss will vary depending on the wavelength.

For example, the loss changes from -31 dB to -68 dB as the wavelength decreases from 375 mm (at 800 MHz) to 5 mm (at 60 GHz) – a range of 37 dB. For cellular frequency ranges the range is 13 dB as the wavelength reduces from 375 mm (at 800 MHz) to 79 mm (at 3,600 MHz).

The Friis formula applies under 'far field' conditions beyond the range of near field interactions with the antenna. It applies to free space or dry open air at frequencies that do not cause resonant absorption by gas molecules such as water vapour of oxygen and other gases.

Far Field assumption applies at distances **d > 2r2/λ** [10] where r is the dimension of the antenna (Table 45).

Carrier Frequency (MHz)	Wavelength λ (mm)	Typical antenna dimension (mm)	Distance from antenna for start of 'far field' propagation $2r^2/\lambda$ (mm)
800	375	800	3,400
60,000	5	5	10

Table 415 - Distance from antenna for 'Far Field' behaviour

The Friis transmission loss formula does not apply to signal propagation within waveguides (Appendix 3.6)

App3.3.2 Effect of additional losses on usable signal propagation range.

Free space loss may be a good proxy for signal propagation within railway tunnels if there is little interaction between the signal and the walls of the tunnel that it reaches (Appendix 3.4).

It is also a helpful proxy, for the same carrier frequency, to estimate the reduction in usable signal propagation range for direct connectivity to passenger devices, considering additional train losses (see Sections 6.2 and 6.3).

Consider the example that a usable signal range of $\mathbf{R_0}$ 2,500 metres is calculated based on a Maximum Allowed Path Loss $\mathbf{L_0}$ 100dB to provide at least -105 dBm locally within a tunnel. If the additional train losses are $\Delta\mathbf{L_t}$ 15 dB then the local tunnel signal level would need to be at least -90 dBm to provide -105 dBm to the passenger devices on board the train.

The signal within the tunnel is at least -90 dBm at a reduced range $\mathbf{R_r}$ where the signal is 15 dB greater.

Rearranging Equation [Eq.A3-1]

$$(\mathbf{R_r} / \mathbf{R_0}) = \sqrt{\frac{path\ loss\ allowance\ \ adjusted\ for\ additional\ train\ losses}{Original\ maximum\ allowed\ path\ loss}} \quad \text{[Eq.A3-4]}$$

In dB logarithmic form:

$$(\mathbf{R_r} / \mathbf{R_0})\ \text{dB} = \mathbf{-0.5} \times \Delta\mathbf{L_t}\ \text{dB} \quad \text{[Eq.A3-5]}$$

Applying equation [Eq.A3-5] the reduced range is a ratio of -7.5 dB smaller than the original range or 18% of the original range. Table 46 shows the great sensitivity of usable range to increasing additional train losses.

Additional Train Losses (dB)	Ratio of reduced range to original range (dB)	Reduced range as % or original range	% Reduction in Range
3	-1.5	71	29
5	-2.5	56	44
10	-5	32	68
15	-7.5	18	82
20	-10	10	90
25	-12.5	6	94
30	-15	3	97
35	-17.5	2	98
40	-20	1	99
50	-25	0.3	99.7
60	-30	0.1	99.9

Table 426 - Reduction in usable range caused by additional train losses (free space loss)

App3.4 Fresnel Zones - effect of obstructions on Huygens' principle of diffraction

While the line-of-sight Friis transmission formula aids calculations between transmitter and receiver in free space, it does not show how sensitive the propagated signal is to diffraction effects caused by any obstruction of the space between transmitter and receiver.

Fresnel applied Huygen's principle (Appendix 3.2) to predict where a physical obstruction may have the greatest impact on propagation and predicted them at ellipsoid Fresnel zones (Figure 31) [11].

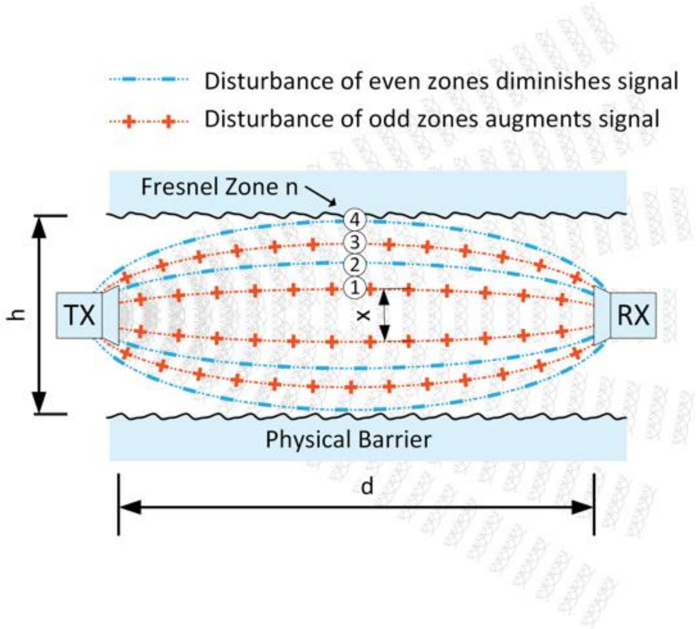


Figure 31 - Fresnel Zones – vulnerability of free space propagation to obstructions

Where the path length would differ from the direct path by a multiple of half wavelengths

nλ / 2 where n is an integer, and λ the wavelength

If **n** is odd, disruption of the Fresnel Zone would tend to increase the signal received by constructive interference.

If **n** is even, disruption of the Fresnel Zone would tend to diminish the signal by destructive interference.

The magnitude of the effect reduces as **n** increases. The formula does not apply if there are multiple physical disturbances between transmitter and receiver.

The maximum diameter **x** of each Fresnel zone is at its mid-point, and is given by the formula

$\mathbf{x} = \sqrt{(\mathbf{n\,d\,\lambda})}$ .... [Eq.A3-6]

Radio planners already apply Fresnel zones to terrestrial link planning to minimise the height of transmission masts. They assume that an obstruction can be tolerated with minimal impact on signal reception if it does not penetrate the first Fresnel Zone by more than 60% of the Fresnel Zone radius.

However, it is the hypothesis of this study that the diameter of the first Fresnel zone is a good indicator of the likely interaction of the signal with the tunnel walls. The Fresnel formula for the maximum diameter of the first zone is consistent with waveguide-based analyses [19] that predict a transitional 'breakpoint distance' **d = x2/λ** between different forms of propagation (Table 47) – this just happens to be the distance into the tunnel at which the diameter of the first Fresnel Zone matches the smallest dimension of the tunnel profile.

Carrier Frequency (MHz)	Wavelength λ (mm)	**Breakpoint Distance (m)** (Dual Track Tunnel h=8m)	**Breakpoint Distance (m)** (Single Track Tunnel h=5m)
800	375	170	67
1,800	167	390	150
2,600	115	550	220
3,800	79	810	320
5,500	55	1,200	460
26,000	11.5	5,500	2,200
60,000	5	13,000	5,000

* **$d = h^2/\lambda$** Also equivalent to the distance between transmitter and receiver where the first Fresnel Zone reaches a diameter of h.

Table 437 - Breakpoint distances

Relevance of Fresnel zones to railway tunnels:

- Fresnel zones offer another diffraction-based mechanism for multi-path fading as the space between transmitter and receiver obstructs increasingly significant Fresnel zones.
- Fresnel zones help to discern the transition between 'Line of Sight' propagation (Appendix 3.3) where the diameter of the first Fresnel Zone is too small to be disturbed by the tunnel walls at all.
- Fresnel zones do not help to explain attenuation behaviour when transmitters and receivers are placed too close to tunnel walls – detailed waveguide analysis is needed instead.

App3.5 Impact of polarisation at boundary of two dielectric media

Detailed analysis of reflectance at a boundary using Maxwell's equations revealed the importance of wave polarisation.

Figure 32 compares two examples of partial reflection. An electro-magnetic ray incident on a material with its electric field vertically polarised, and in the same plane of reflection as the ray, will be partially reflected. Reflectance diminishes to zero at the Brewster Angle (also known as the polarisation angle) where:

$\theta_B = \arctan(n_2/n_1)$ .... [Eq.A3-7]

Only linearly polarised light is transmitted through the boundary. The effect does not occur for horizontally polarized light where the Electric field lies parallel to the plane of reflection.

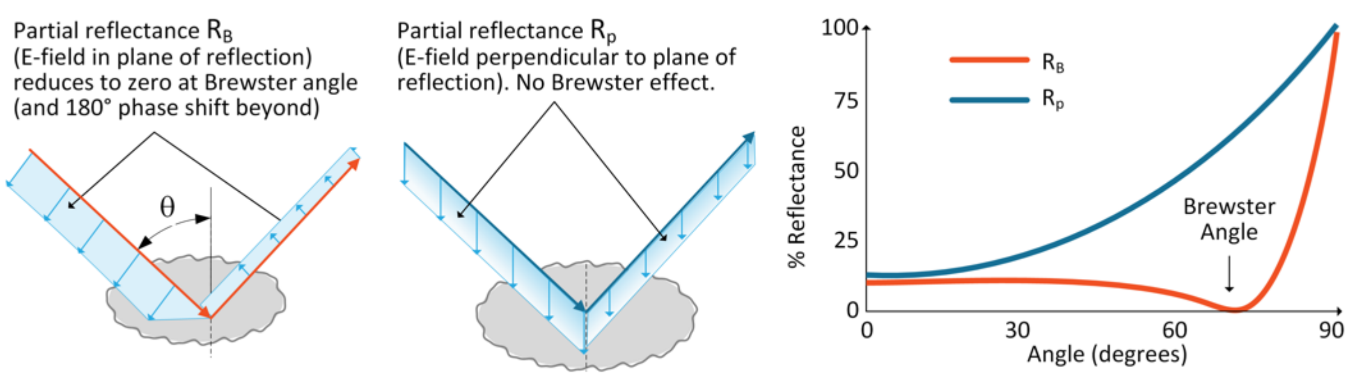


Figure 32 - Impact of Polarisation on reflectance at boundary

This means that each reflection or interaction of a signal with the railway tunnel surface influences its polarisation whatever that emitted by the transmitter. This may degrade the effectiveness of cross-polarised MIMO Directional Antennas in longer tunnels (Section 4.3.2). The polarisation also affects the phase of reflected waves and hence also multi-path fading.

App3.6 Waveguides and their propagation modes

The role of waveguides, based on Maxwell's equations [9], has already been introduced in Section 5.1. This Section illustrates with examples of relevance to signal propagation through railway tunnels.

Electromagnetic waves in free space travel as transverse electromagnetic waves (TEM) at the speed of light and where the Electric (x-axis) and Magnetic fields (y-axis) are locked at right angles (orthogonal) to each other and the direction of propagation (z axis). Power transfer in the z-axis is equal to $\mathbf{E} \times \mathbf{H}$ the Poynting Vector and is analogous to ray tracing (Appendix 3.1).

Propagation within waveguides is more constrained as a finite set of propagation modes consistent with the boundary conditions. In practice this means that TEM waves are not allowed. Only one of the E or H field vectors can be orthogonal to the direction of propagation – the other vector must have a component along the z-axis. Modes of propagation must either be Transverse Electric (TE) or Transverse Magnetic (TM) waves.

Figure 33 shows some typical low order modes for hollow metallic rectangular and circular wave guides. The cross section of most rail tunnels comprises elements of both so indicate the complexity of mode field shapes.

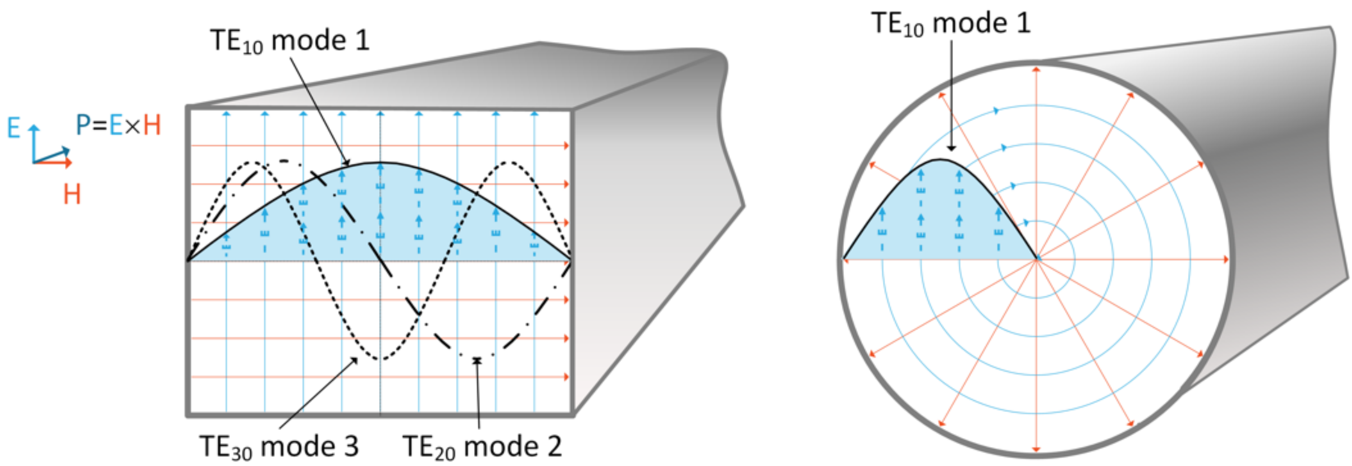


Figure 33 - Typical modes supported by hollow metallic waveguides

Figure 34 shows the propagation mode of a single mode optical fibre. Since it is all dielectric, the E and H fields are not clamped at the boundary between core and cladding but must ensure a smooth transition. Optical fibres are all-dielectric but very different to a hollow tunnel as already discussed in Section 5.1 [12, 13, 14].

Dielectric waveguide – optical fibre

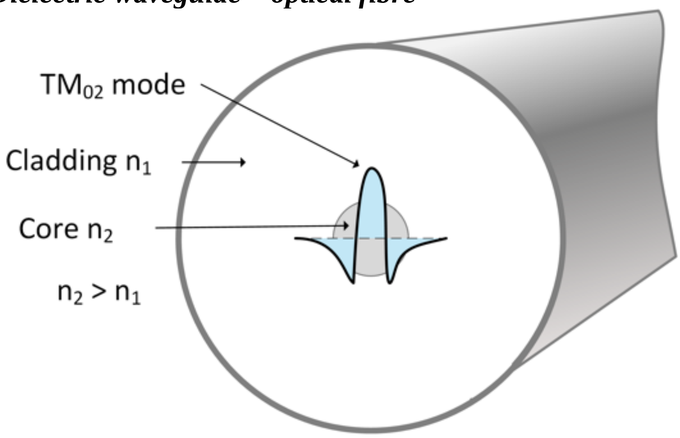


Figure 34 – Single-mode optical fibre

RF waveguides can support the propagation of any electromagnetic radiation above a cut of frequency linked to the tunnel cross section. So, a tunnel of dimension 6 metres will not propagate wavelengths greater than 12 metres, or frequencies below approximately 25 MHz. Signal can propagate both forwards and backwards leading to standing waves (another potential cause of signal fading) if the impedance and polarisation of the source and receiver are mismatched, or if there are abrupt changes along the wave guide. Waveguide boundaries, dimensions, and materials constrain the distribution of electric and magnetic fields within the waveguide space to a finite set of propagation modes. The waveguide influences the speed at which each mode can propagate and the rate at which each mode attenuates with distance for a given signal wavelength and typically exponentially (straight line on a log signal versus linear distance dB versus distance in metres chart).

Railway tunnels, like optical fibres, are dielectric waveguides comprising a transparent core and cladding of different refractive indices. However, there are major differences between an optical fibre and a railway tunnel including differences in optical boundary, the size of the core, the quality of the boundary, and control of source and receiver coupling [58, 59, 60]:

- The core of an optical fibre has a higher refractive index than its cladding to support low loss propagation by total internal reflection. From a ray perspective, signal is reflected along the fibre at a glancing angle to the wall of the core and experiences total internal reflection. Rays can bounce up and down along the core as meridional rays or corkscrew around as skew rays[iv]. Rail tunnels are the opposite to optical fibre, with a lower refractive core and so act as lossy hollow waveguides.

  A large proportion of signal will be lost constantly by partial transmission and refraction into the tunnel walls. The tunnel walls will absorb a little power because of electrical conduction within the tunnel surface. Glancing rays will enjoy a higher reflectance than others but never achieve total internal reflection. At wireless frequencies, the reflectance is also polarisation sensitive (Brewster Angle – Appendix 3.5), so the polarisation of the signal becomes determined by the tunnel geometry rather than the transmitting antenna.

- Modern communication optical fibres are designed with a small core that allows only one mode to propagate at the near infrared wavelengths used (Figure 34). This trades a small initial signal coupled into the fibre in exchange for very low signal dispersion, allowing the maximum data rate. A railway tunnel is large and able to support hundreds if not thousands of modes. It is vulnerable to substantial signal dispersion as each mode travels at different speeds. In practice, the effect is reduced because large numbers of higher modes attenuate very rapidly before the dispersion can accumulate and dispersion over longer distances is reduced as the signal is carried by a diminishing number of modes (one paper suggested approximately 40 active modes at 100 metres reducing to four modes at 1,000 metres [21]).

- Rail tunnels present a far rougher optical boundary than within an optical fibre. Random variations in geometry and material properties lead to diffuse reflection and diffractions (see Appendix 3.7) mixing signal between the modes. This both increases signal attenuation by converting low modes into lossier higher modes, and the difficulty of characterising the properties of tunnel surfaces for predictive modelling as they must be treated as random variables.

- Optical fibres are fed by point source laser diodes, but these are aligned with precision to optimise coupling of light into the wave guide. Railway tunnel wave guides are illuminated by a combination of sources. Portal and distributed antennas are point sources. Near portal antennas illuminate the tunnel entrance with a diffuse signal. Radiating cables present a line source along the length of the tunnel. It is difficult to predict how much energy is coupled into the many possible propagation modes (see Appendix 3.8).

All these factors combine to offer explanations for the characteristics observed during RF test:

- Erratic signal fading throughout the range may be explained by Huygen's diffraction (Appendix 3.2) and interference, including Fresnel zone effects (Appendix 3.4), mixing of phase-shifted rays, interference between modes or even waveguide standing waves from forward and backwards travelling waves (Appendix 3.6). Such effects can also occur because of interaction with the tunnel approach and portal features. These effects may lessen with distance into the lossy dielectric tunnel as fewer modes persist deep into the tunnel that are able to interfere (Section 5.2).

- Erratic changes in signal may also be linked to changes in alignment of transmit and receive antenna with range, particularly for the highest frequencies (millimetre waves). The RF test measurements were made with a receiver on the end of a flexible pole with variations in antenna position and alignment determined by a hand pushed trolley or trailer towed by a road-vehicle.

- The overall attenuation range characteristic may decline rapidly initially as higher order modes are refracted and lost into the walls of the tunnel. Deeper into the tunnel the propagation of fewer modes will be sustained and tend to decay exponentially (linear dB loss versus distance) (Figure 26).

- Lower band frequencies (longer wavelengths) may be radiated more efficiently by a transmitter initially but will interact sooner with the walls of the tunnel (Fresnel Zones – Appendix 3.4), despite being less affected by smaller random variations in the tunnel surface as they cannot be resolved if smaller than a tenth of a wavelength. Lower frequencies interact sooner and propagate as lossier modes. Higher cellular frequencies should propagate better as modes unless disrupted by high levels of scattering at rough and uneven surfaces.

- The observations most difficult to explain are the sudden recovery of signal levels up to 10 dB stronger 1,200 metres into Standedge Old Tunnel at 1,800 MHz (Figure 51 in Appendix 4). A lossy waveguide should experience continuous loss of overall signal power and decay monotonically along its length in the absence of standing waves or fading effects. One explanation may be that the receiver starts to couple to a greater proportion than the modes present. It is not clear if this is the result of waveguide behaviour (modal mixing) or simply a sudden change in the alignment of the receive antenna.

App3.7 Effect of random variations in geometry and material properties

Any surface imperfections greater than one tenth of the wavelength of the radiation (greater than **λ / 10**) [10] will lead to diffuse reflection at optical boundaries.

Regular imperfections may compound diffraction effects. Random imperfections will reflect and refract in random directions (Figure 35). This will increase signal attenuation because any rays scattered at angles lower than the incident ray θ will be more likely to be absorbed. From a Maxwell perspective, some lower mode signal power is converted into lossier higher modes. This also complicates mathematical modelling that needs to deal with functions of random variables.

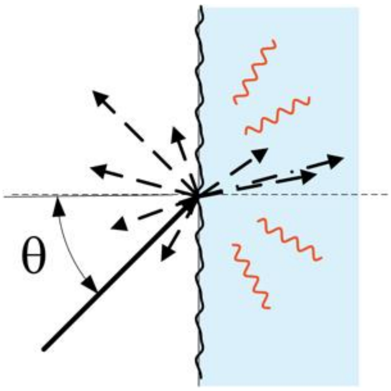


Figure 35 - Diffuse reflection, refraction and absorption at a rough dielectric boundary

Real materials used in railway tunnel walls are not homogeneous and may exhibit changing electrical permittivity and magnetic permeability (see box at start of Section 5) that are frequency dependent and affected by electrical conductivity that dissipates a small proportion of the signal as heat within the tunnel walls.

While bare rock will vary randomly, brick or masonry pointing, and linings constructed by standard concrete segments, present regular repeating patterns that may affect propagation. The magnetic permeability of steel or iron lining elements will also have an effect.

App3.8 Antennas as waveguide coupling components

The design of antenna relies on the direct application of Maxwell's equations. Most directional antenna designs are derived from analysis of the magnetic dipole, a theoretical tiny linear conductor maintaining a time-varying electric current along one axis and the electric and magnetic fields associated with the current. By varying the length of the dipole and adding additional passive components, antennas with complex propagation patterns can be created (Figure 36).

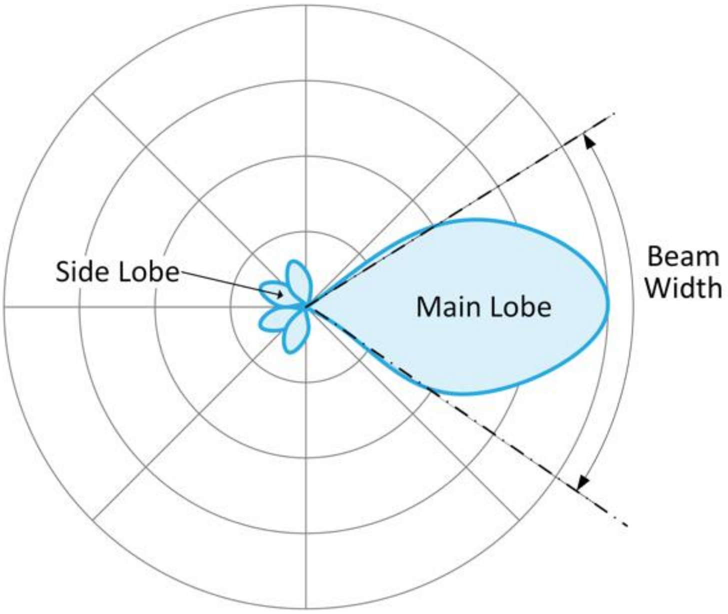


Figure 36 - Typical azimuthal polar diagram of directional antenna

Some of the complexity such as side lobes and differences between 'near field' interactions and 'far field' free propagation effects are inevitable and predicted by Maxwell, but other features are deliberately engineered. Radio planning engineers seek directionality or gain (Appendix 3.3), often across a broad range of frequencies that also influence the antenna beam width. The beam width of an antenna is simply defined as the angular range within which the signal power density achieves at least 50% of peak (-3 dB), so signal is also directed in wider directions.

The amount of signal that can be propagated will also depend on other aspects of electrical system design. Impedance matching is needed to optimise forward transmission and minimise reflection and the creation of standing waves. The geometry of the antenna may also be used to control the polarisation of the signal.

Relevance to propagation within railway tunnel:

- The actual behaviour of point antennas at tunnel portals or as distributed antenna systems within tunnels may be influenced by interaction with the tunnel as a waveguide, varying their engineering characteristics, for example, gain. This will also determine how signal power is coupled into the propagation modes supported by the tunnel (Appendices 3.4 and 3.6) and similarly by any receiver within the tunnel.

- Tunnel surfaces may also impose signal polarisation as well as the antenna, especially as the signal penetrates deeper into the tunnel after multiple reflections. This may affect the correlation of data streams transmitted by cross-polarised antennas used in a MIMO setup (Section 4.3.2).

Appendix 4
Radio-Frequency Field Testing

This Appendix presents information in support of Section 7.5 of the main text.

App4.1 RF test locations

The study team carried out RF signal propagation loss measurements at three non-operational brick-lined tunnels at Dudley in the West Midlands operated by the Black Country Innovative Manufacturing Organisation (BCIMO), Standedge Old Tunnel running through the Pennines between Diggle in Greater Manchester and Marsden in West Yorkshire, and Copenhagen tunnel on the approach of the East Coast mainline into London Kings Cross (Figure 37).

Both Standedge (Old) and Copenhagen tunnels are owned and operated by Network Rail and its subcontractors.

Dudley	**Standedge (Old)**	**Copenhagen**
 a) Fixed transmitter, receiver on rail trolley (Dudley)	 b) Fixed transmitter at portal (Standedge)	 c) Portal obstructed by other contractors' vehicles and cabins (Copenhagen)
 d) Dudley Tunnel (north)	 e) Near portal transmittal setup showing steel portal frame at tunnel entrance (Standedge).	

Figure 37 - Signal Propagation Loss setups by tunnel

Table 48 compares the test conditions encountered at the three test locations and the techniques used to 'sweep' each tunnel for signal propagation loss.

Tunnel	Dudley	Standedge (Old)	Copenhagen
Length	844 metres	4,890 metres	540 metres
Construction	Brick-lined bore, 1852	Brick-lined bore, 1848	Brick-lined bore, 1886
Size	T3 / T4 7.9m wide by 6.1m high Dual track (only one fitted)	T1 5m wide by 5m high Single track (none fitted)	T3 / T4 7.9m wide x by 6.1m high (outer masonry portal) (inner portal ~3.5m in from outer) Dual track (none fitted)
Alignment	Straight from southern portal Curved from northern portal (radius = 805 m)	Straight	Straight
Receiver setup	Mounted on rail trolley, pushed along track at a steady speed	Mounted on trailer towed by road vehicle or pushed manually. Height of antenna moved up and down with ground irregularities. Also had to be lowered to fit under metal structure at least 1km into tunnel Omni-directional antenna up to 6 GHz Beamwidth 30° @ 26 GHz for both transmitter and receiver.	Mounted on trailer pushed manually
Measurement conditions within tunnel	Dry and well lit. Some corrugated steel repairs to roof	Deep potholes within the remaining track bed filled with ground water.	Dry, lit but with ventilation equipment. Contractors' vehicles and plant obstructing the tunnel portal.
External measurement conditions (Near Portal measurements)	OK	Metal gates. Metal portal frame just outside portal.	NA
Effect on measurements	NA	NA	NA
Mitigations	NA	Vehicle driven slowly.	NA

Table 48 - Differences in Test Conditions by tunnel

App4.2 RF test setup and scenarios

App4.2.1 Test Equipment

The test equipment used is listed in Table 49.

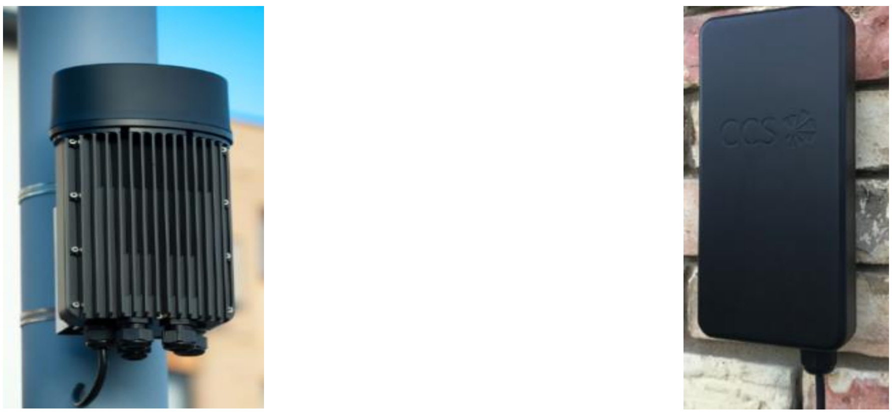
Description	Frequency Range	Make/ Model
Signal Generator	9 kHz to 40 GHz	Keysight N5173B RF EXG
58 GHz functional transmitter and receiver pair	Nominally 58 GHz	CCS Met 60G (Mesh and CPE) [46, 47]
Spectrum Analyser 9 kHz to 43 GHz	9 kHz to 43 GHz	Anritsu MS2726C Field Spectrum Analyser
Tx Antenna (Vertical polarisation)	700 MHz to 6 GHz	HyperLog 7060 Log Periodic Vertical polarisation Antenna gain 5 to 6 dBi (frequency dependent) Beam width > 35°
Rx Antenna (Vertical polarisation)	800 MHz to 6 GHz	Cobham DS1665 omnidirectional broadband Antenna gain 0 to 4.9 dBi (frequency dependent) Beam width 360° (azimuthal)
Tx and Rx waveguide standard horn antenna (Vertical polarisation)	18 to 26.5 GHz	PE9852B/2F-15 WR-42 Antenna gain 15 dBi Beam width 31.5°

Table 449 - Schedule of calibrated test equipment

Signal Propagation loss was measured based on the Friis transmission formula described in Appendix 3.3 and the power link analysis illustrated in Appendix 2.2, based on calibration data supplied for the signal generator, spectrum analyser, antennas, and feeder cables. Basic functional testing was carried out at the start of each test setup, both in the lab and on-site, by comparing measured and theoretical free space loss with the test transmitter and receiver in-line and separated by a known distance (1-3 metres) to confirm that actual system losses were consistent with that expected by the calibration data. RF cables, excluding the antennas, were also tested directly by looping from signal generator direct to signal analyser.

The receiver analyser was set to run single sweep or trigger to record the signal level. The sweep measurements were saved on the spectrum analyser as well as recorded on the measurement excel sheet.

No formally calibrated equipment was available for hire at 60 GHz. Instead, elements from a commercial mesh network provider, Cambridge Communications Systems Ltd (CCSL) was used. The transmitter comprised a mesh node as transmitter operating at 58.32 GHz and was used with a Customer Premises Equipment (CPE) node configured as a receiver. The manufacturer advised how to select fixed transmit power, frequency band and bandwidth at the transmitter and monitor received signal strength levels at the receiver. Careful manual alignment was required because of the narrow beam width and measurements only attempted at Dudley (south) and Standedge Old tunnels.



a) 58.32GHz Mesh transmitter b) 58.32GHz CPE receiver

Figure 38 - Signal Propagation Loss setup: 60GHz proprietary active antennas

App4.2.2 Test Scenarios

Measures to recreate transmission from a Near Portal (S1) mast used the transmit antenna mounted on a pole and positioned approximately 45 metres from the tunnel portal and offset by approximately 4 metres from the measurement centre at an angle of 5° (equivalent to the layout shown in Figure 11). The antenna was pointed towards the intersection of the measurement centreline and the tunnel portal.

All test measurements measured signal propagation loss with respect to a fixed transmitter location as a receiver was pushed or towed into each test tunnel at a continuous wave spot frequency and seeking to maintain the same position with the cross section of each tunnel.

The variety of transmitter and receiver locations are shown in Figure 39. Dudley was chosen to assess a typical dual track bored brick arch tunnel, straight from the South but with a curve towards the North and was fitted with one track.

Standedge (Old) is a long straight single bore brick arched tunnel with an empty track bed. It is part of a complex of parallel tunnels co-owned by the Canal & River Trust and Network Rail.

Copenhagen Tunnel is a shorter straight dual track brick-arched tunnel currently being brought back into use on the ECML. It was used to corroborate the Dudley tests and to explore how sensitive signal propagation loss was to tunnel and receiver location.

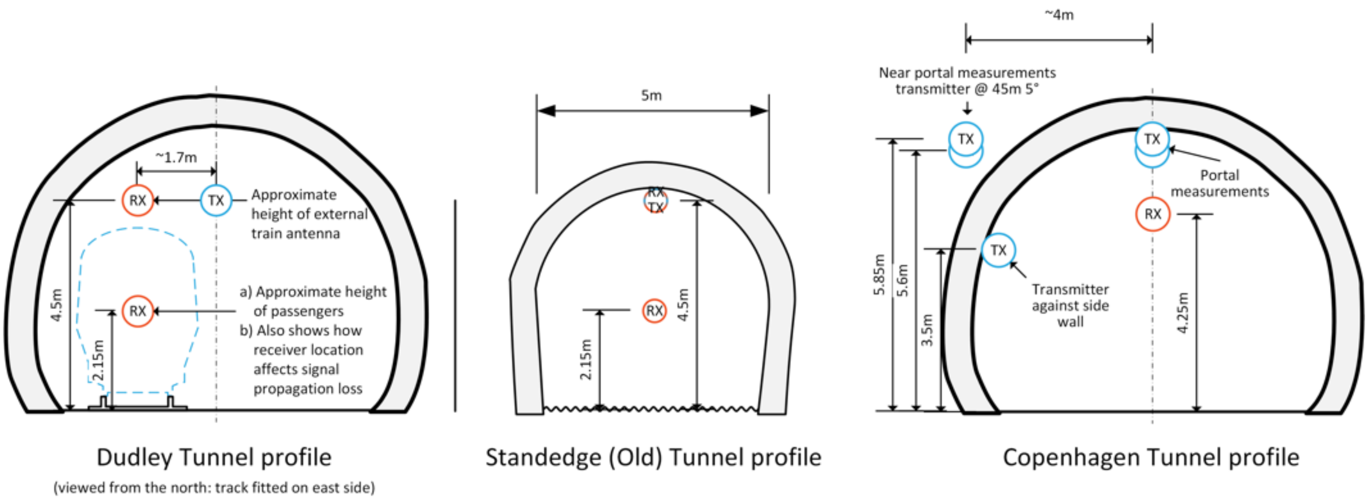


Figure 39 - RF test transmitter and receiver locations at each tunnel

The mix of transmitter and receiver locations assessed is illustrated in Figure 39 with a detailed schedule of scenarios measured in Table 50.

Tests were carried out up to eight spot frequencies. Frequencies greater than 5 GHz were deemed only appropriate for direct line of sight operation to an external train antenna mounted at roof height on train ends as part of an indirect on-train gateway solution and train-based gateway servicing passenger devices on the train, so no measurements were carried out at a receiver height of 2.15 metres for these frequencies.

App4.3 RF Test measurement results

Table 50 overleaf presents a schedule of measured signal propagation loss characteristics at Dudley, Standedge (Old) and Copenhagen tunnels followed by the signal propagation loss (dB) versus distance charts (Figures 40 to 61).

Test Scenario	See Figure	TX height	RX height	Sweep	890 MHz	1,801 MHz	2,590 MHz	3,510 MHz	5,500 MHz	26 GHz	58.32 GHz	Comments
Dudley (South) Straight												
1 Near Portal (external train antenna)	40	4.5m located 45m at 5°	4.5m	Rail trolley	Y	Y	Y	Y	Y	-	-	[TS4a] external train antenna
	41				-	-	-	-	-	Y	-	[TS4a] external train antenna
2 At Portal (external train antenna)	42	4.5m	4.5m	Rail trolley	Y	Y	Y	Y	Y	-	-	[TS1a] external train antenna
	43				-	-	-	-	-	Y	-	[TS1a] external train antenna
	44				-	-	-	-	-	-	Y	[TS1a][v] Follows free space Loss adjusted for predicted additional O_2 absorption 12.9 dB/km
Dudley (North) Curved												
3 Near Portal (external train antenna)	45	4.5m located 45m at 5°	4.5m	Rail trolley	Y	Y	Y	Y	Y	-	-	[TS4a] external train antenna
	46				-	-	-	-	-	Y	-	[TS4a] external train antenna
4 Near Portal (external train antenna)	47	4.5m located 45m at 0°	4.5m	Rail trolley	Y	Y	Y	Y	Y	-	-	[TS4b] external train antenna
5 At Portal (external train antenna)	48	4.5m	4.5m	Rail trolley	Y	Y	Y	Y	Y	-	-	[TS1a] external train antenna
	49				-	-	-	-	-	Y	-	[TS1a] external train antenna
6 At Portal (direct connectivity)	50	4.5m	2.15m	Rail trolley	Y	-	Y	-	Y	-	-	[TS1b] Direct connectivity
Standedge Old												
7 Near Portal (external train antenna)	51	4.5m located 45m at 5°	4.5m	Vehicle towed	Y	-	Y	Y	Y	-	-	[TS4a] no1800
8 At Portal (external train antenna)	52	4.5m	4.5m	Vehicle towed	Y	Y	Y	Y	Y	-	-	[TS2a] potentially anomalous 1801 from 1200m
	53			Vehicle towed	-	-	-	-	-	Y	-	[TS2a]
	54			Pushed trolley	-	-	-	-	-	-	Y	[TS1a] 2 x runs 40m and 150m [slightly better than free space loss perhaps due to more waveguiding in narrower tunnel
9 At Portal (Direct connectivity)	55	4.5m	2.15m	Pushed trolley	Y	Y	Y	-	Y	-	-	[TS1b]

Table 45 - Schedule of Test Measurements

Test Scenario	See Figure	TX height	RX height	Sweep	890 MHz	1,801 MHz	2,590 MHz	3,510 MHz	5,500 MHz	26 GHz	58.32 GHz	Comments
Copenhagen												All for external train receiver
10 Near Portal	56	5.85m located 45m at 5°	4.25m	Vehicle towed	Y	Y	Y	Y				[TS4a1
11 Near Portal (lower transmitter)	57	5.6m located 45m at 5°	4.25m	Vehicle towed	Y	Y	Y	Y				[TS4a2]
12 At Portal	58	5.85m at outer portal	4.25m	Vehicle towed	Y	Y	Y	Y				[TS422a.1]
13 At Portal (lower transmitter)	59	5.6m at outer portal	4.25m	Vehicle towed	Y	Y	Y	Y				[TS422a.2]
14 3.5m Inside Portal	60	3.5m located 3.5m inside outer portal at side wall	4.25m	Vehicle towed	Y	Y	Y	Y				[TS422b]
15 20m Inside Portal	61	5.6m located 20m inside outer portal	4.25m	Vehicle towed	Y	Y	Y	Y				[TS423a.1]

Table 50 (cont.) - Schedule of Test Measurements

Dudley (South) Straight

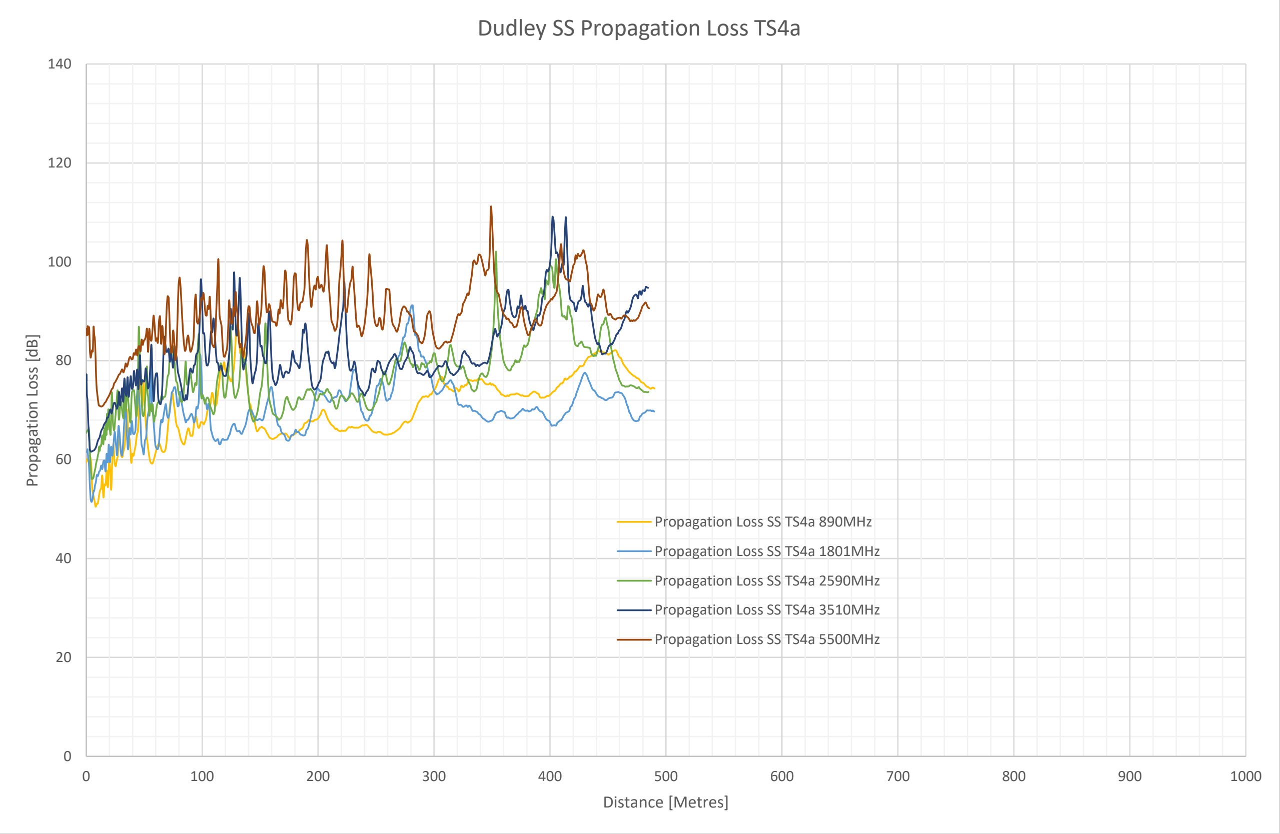


Figure 40 - [TS4a] Signal Propagation: Dudley (South-Straight) Near Portal solution (external train antenna) up to 6GHz

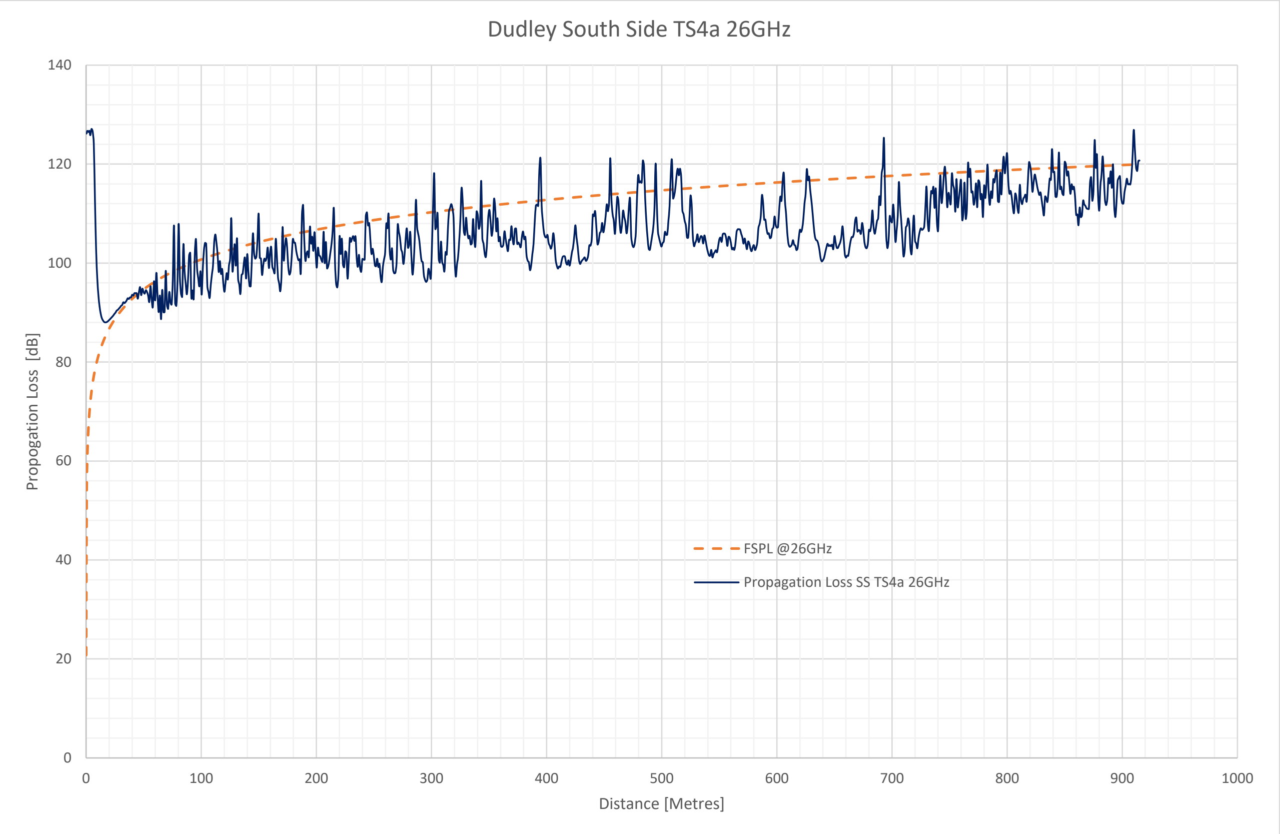


Figure 41 - [TS4a] Signal Propagation: Dudley (South-Straight) Near Portal solution (external train antenna) 26GHz

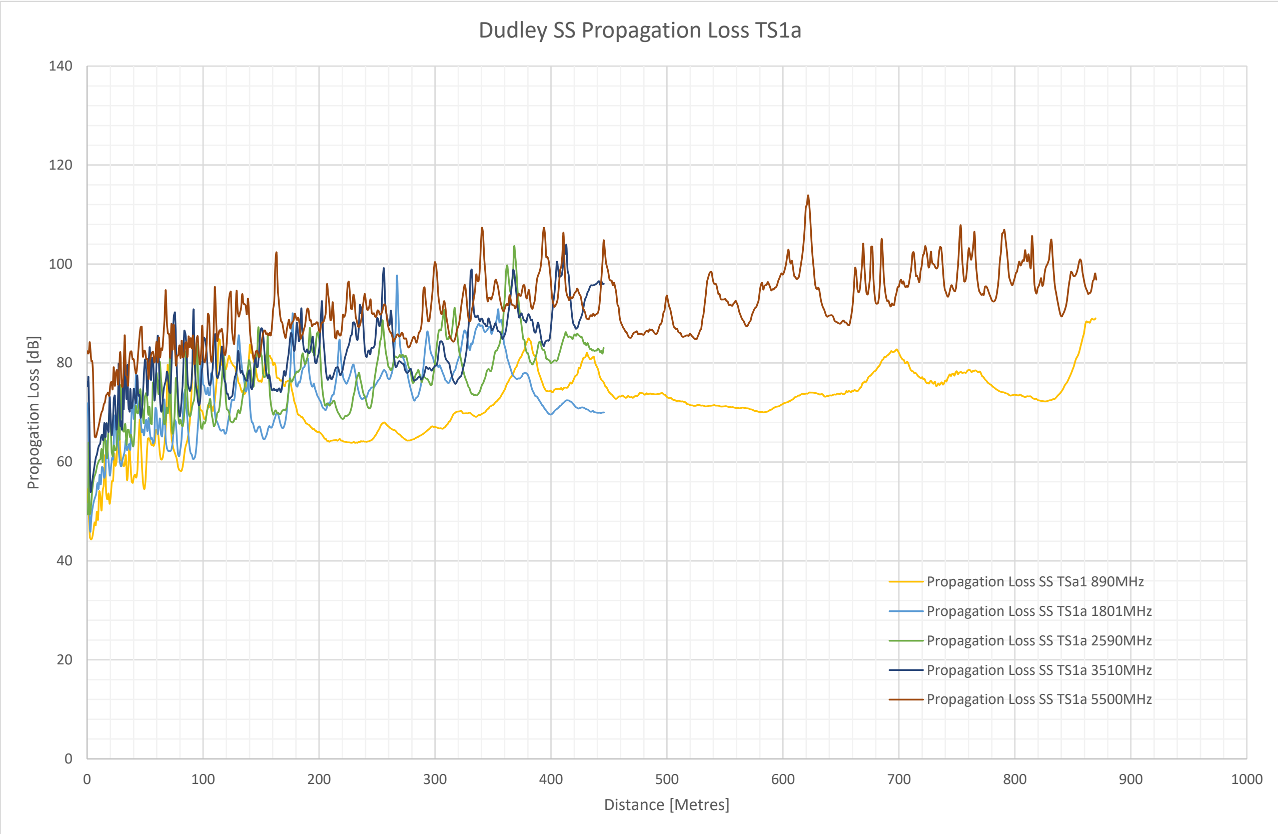


Figure 42 - [TS1a] Signal Propagation: Dudley (South-Straight) At Portal solution (external train antenna) up to 6GHz

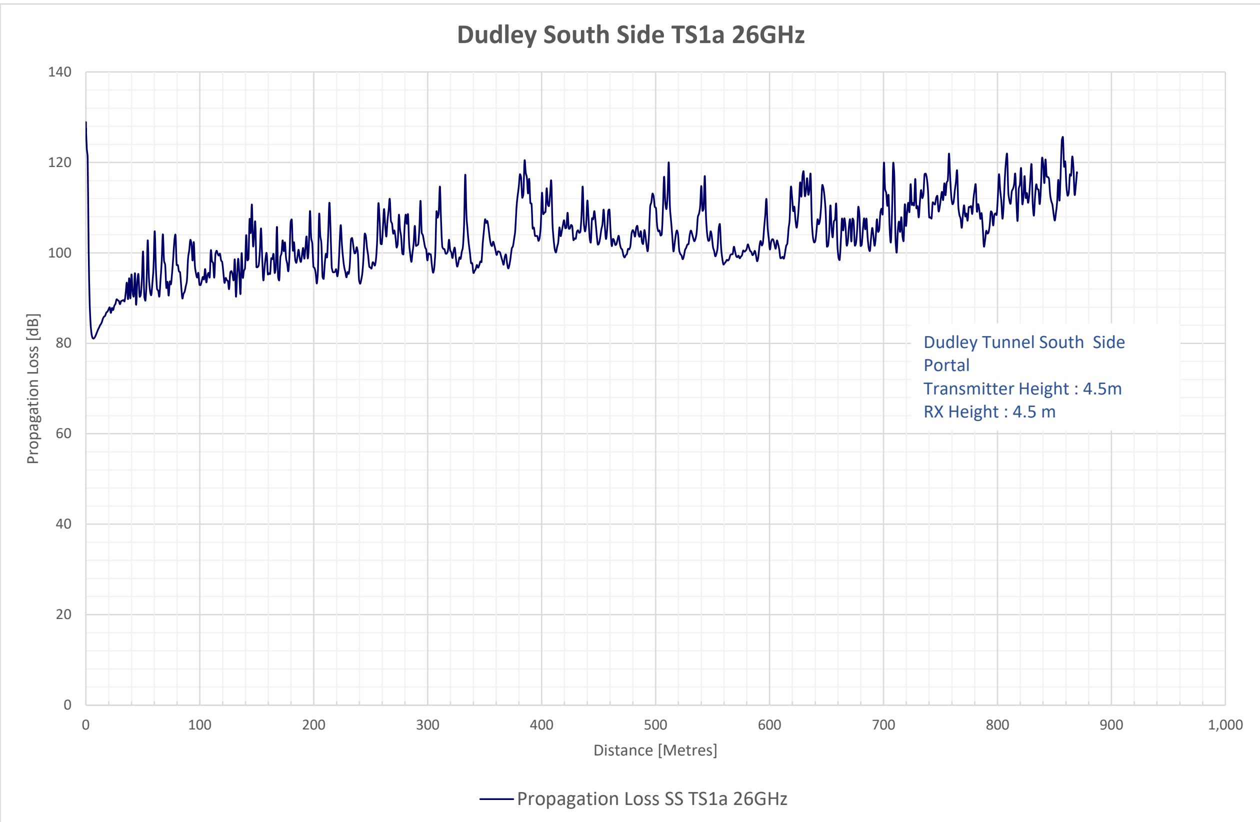


Figure 43 - [TS1a] Signal Propagation: Dudley (South-Straight) At Portal solution (external train antenna) 26GHz

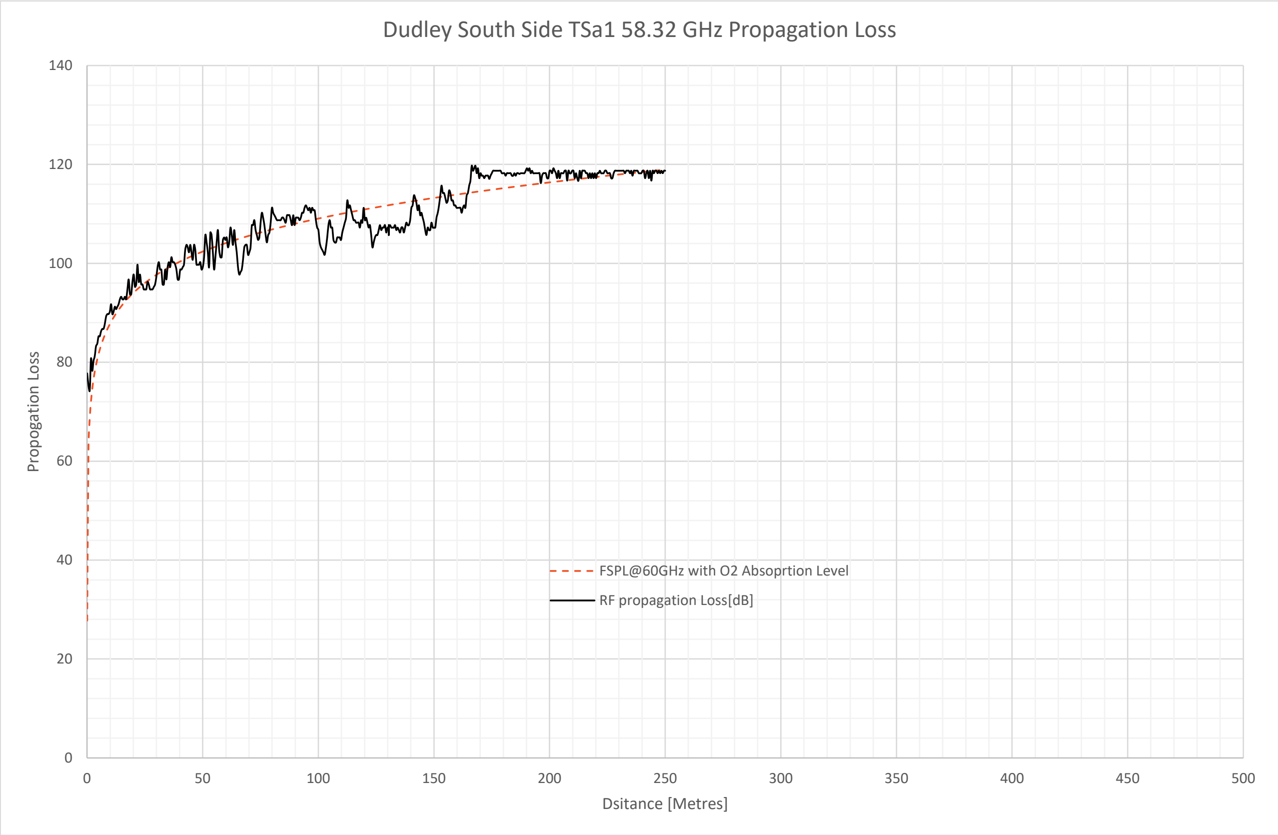


Figure 44 - [TS1a] Signal Propagation: Dudley (South-Straight) At Portal solution (external train antenna) 58.32GHz

Dudley (North) Curved

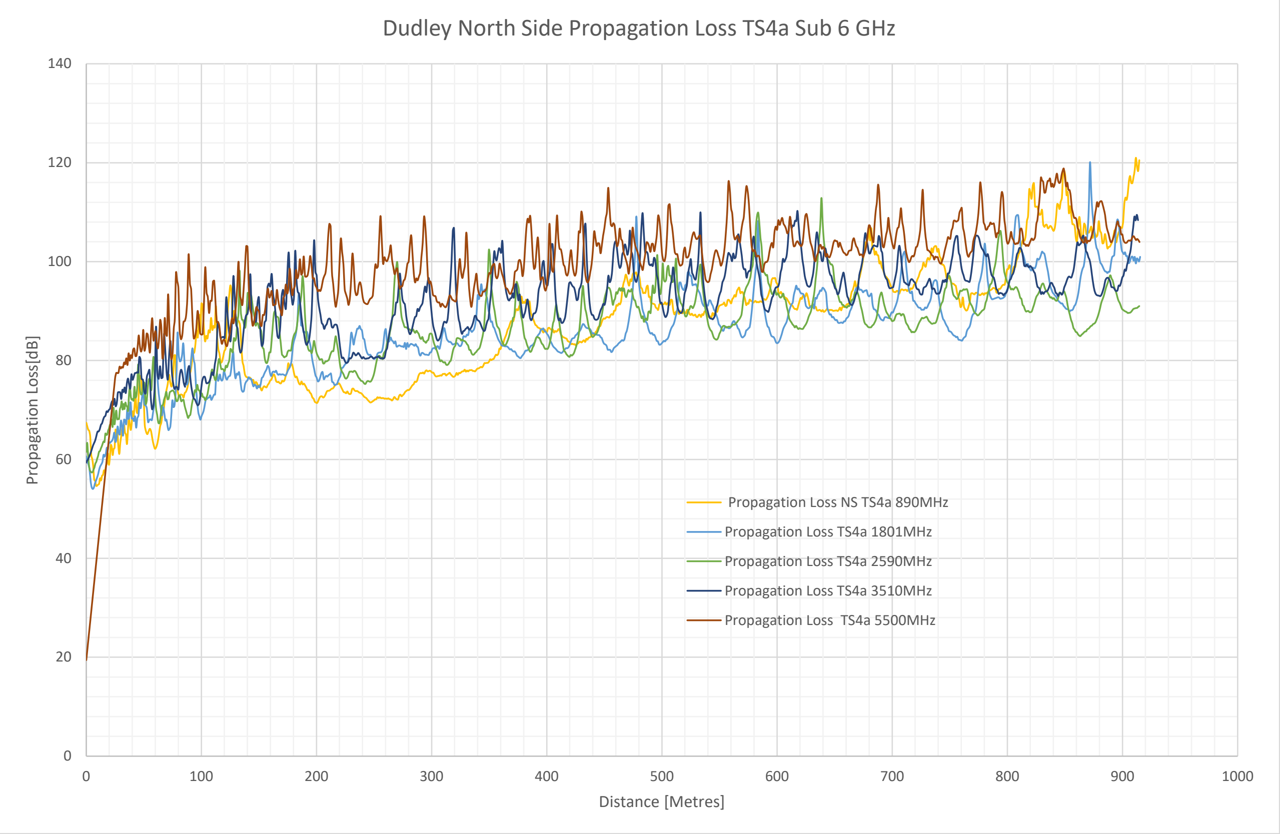


Figure 45 - [TS4a] Signal Propagation: Dudley (North-Curved) Near Portal solution 45m at 5° (external train antenna) up to 6 GHz

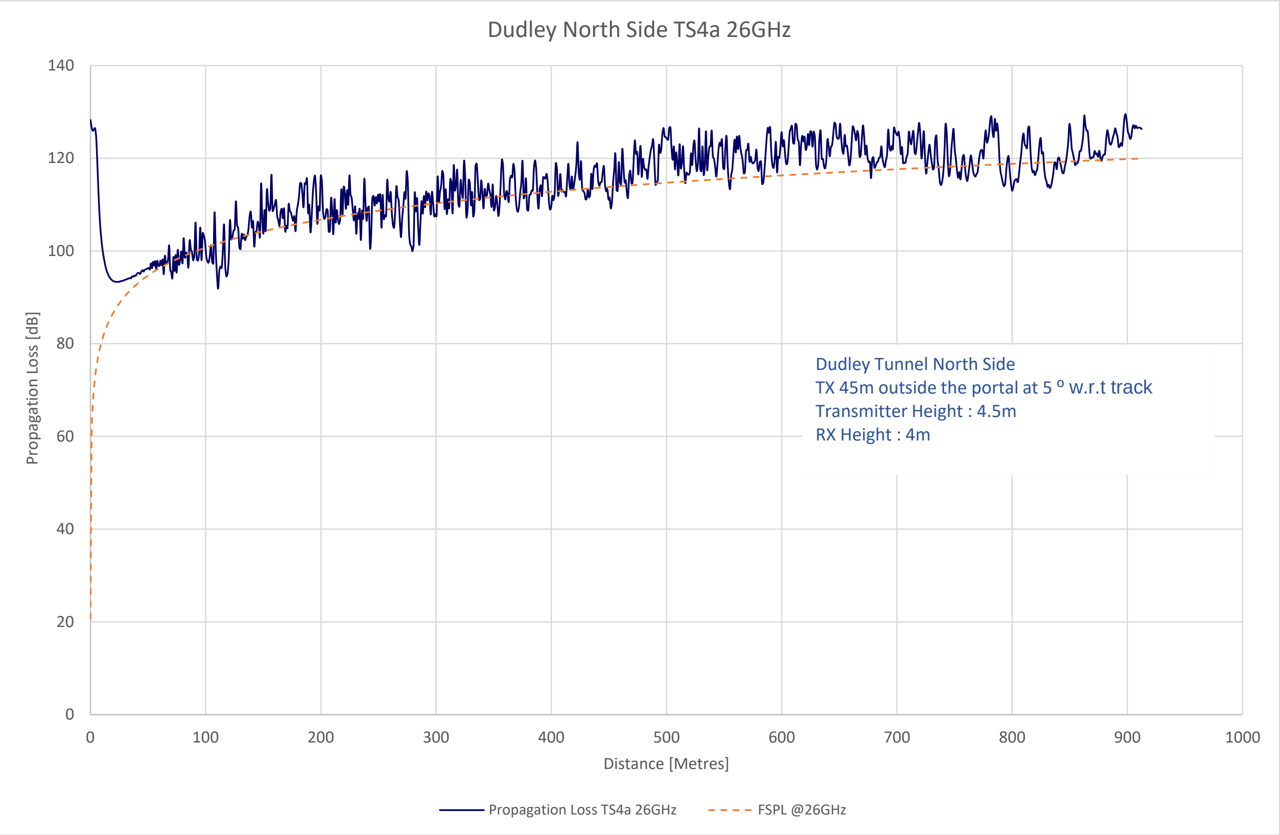


Figure 46 - [TS4a] Signal Propagation: Dudley (North-Curved) Near Portal solution 45m at 5° (external train antenna) 26GHz

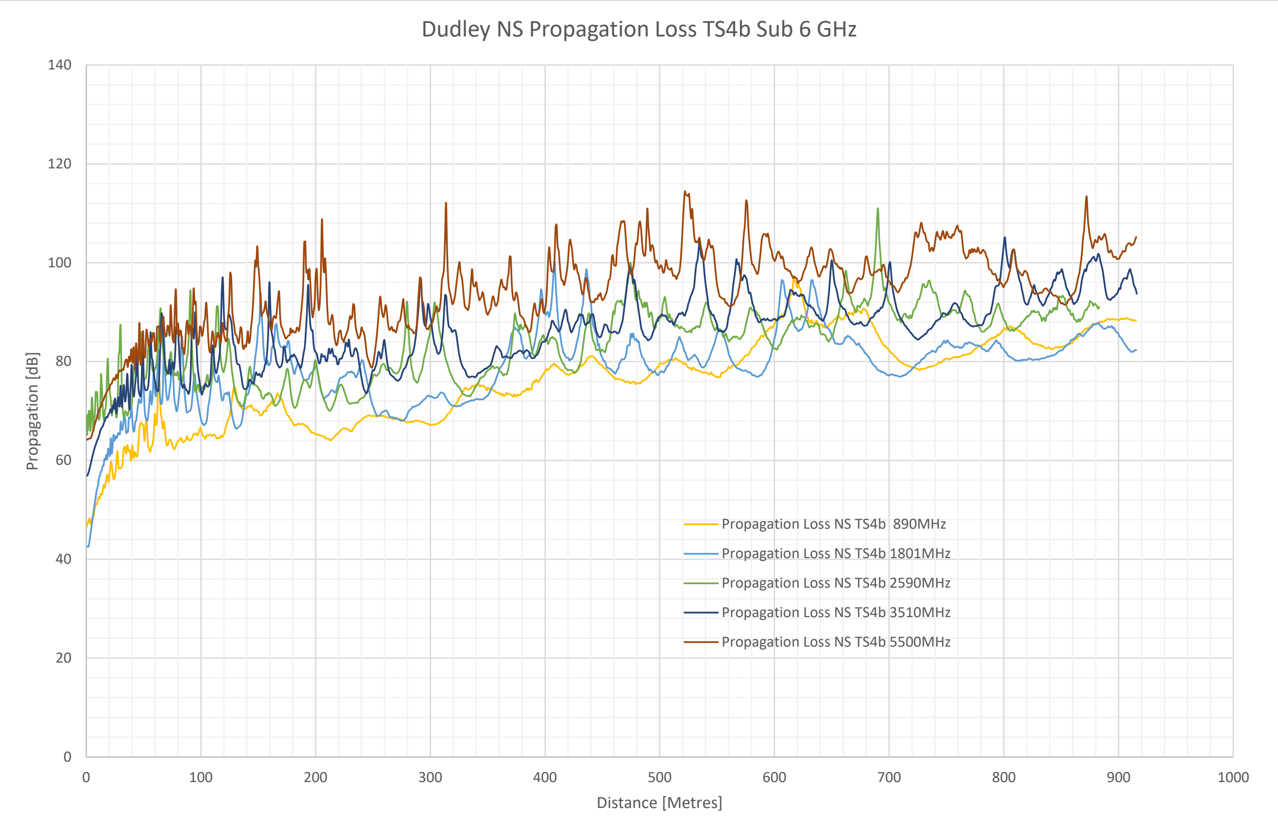


Figure 47 - [TS4b] Signal Propagation: Dudley (North-Curved) Near Portal solution 45m at 0° (external train antenna) up to 6GHz

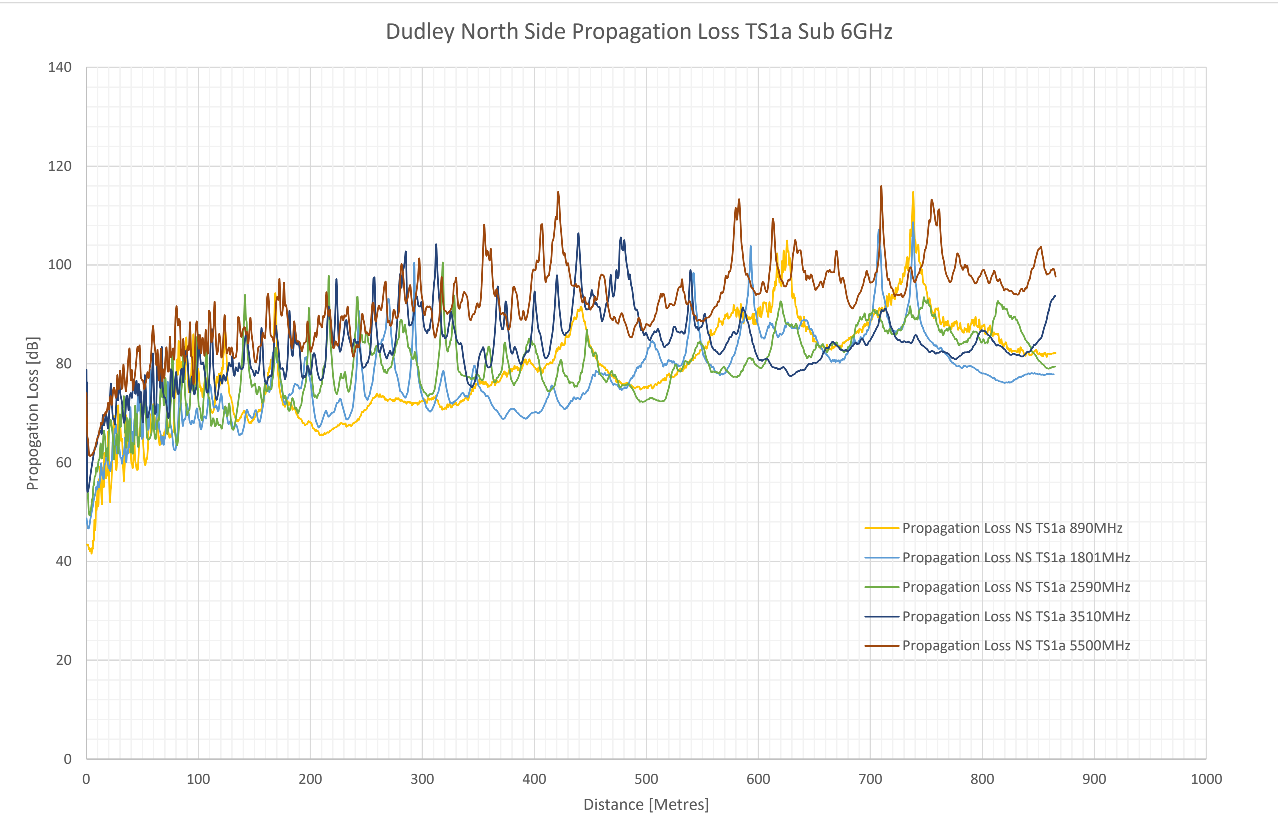


Figure 48 - [TS1a] Signal Propagation: Dudley (North-Curved) At Portal solution (external train antenna) up to 6GHz

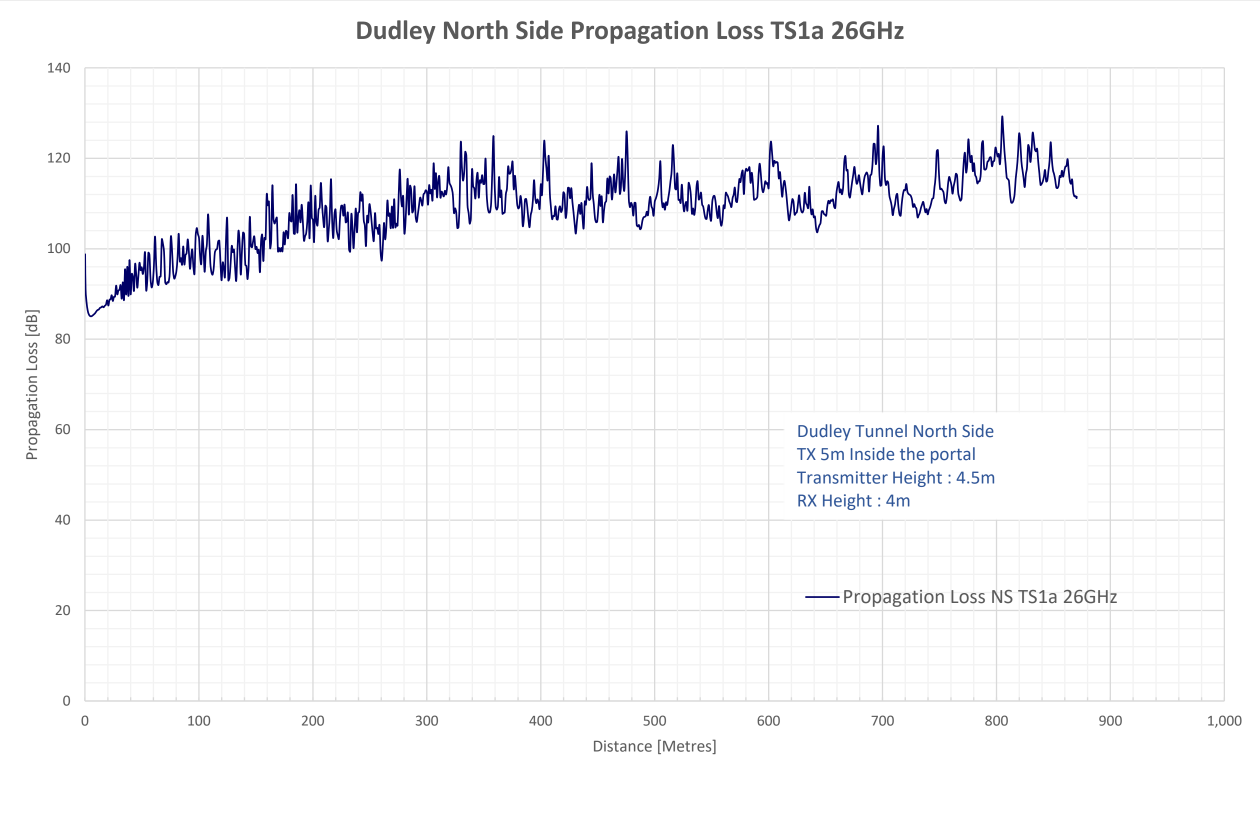


Figure 49 - [TS1a] Signal Propagation: Dudley (North-Curved) At Portal solution (external train antenna) 26 GHz

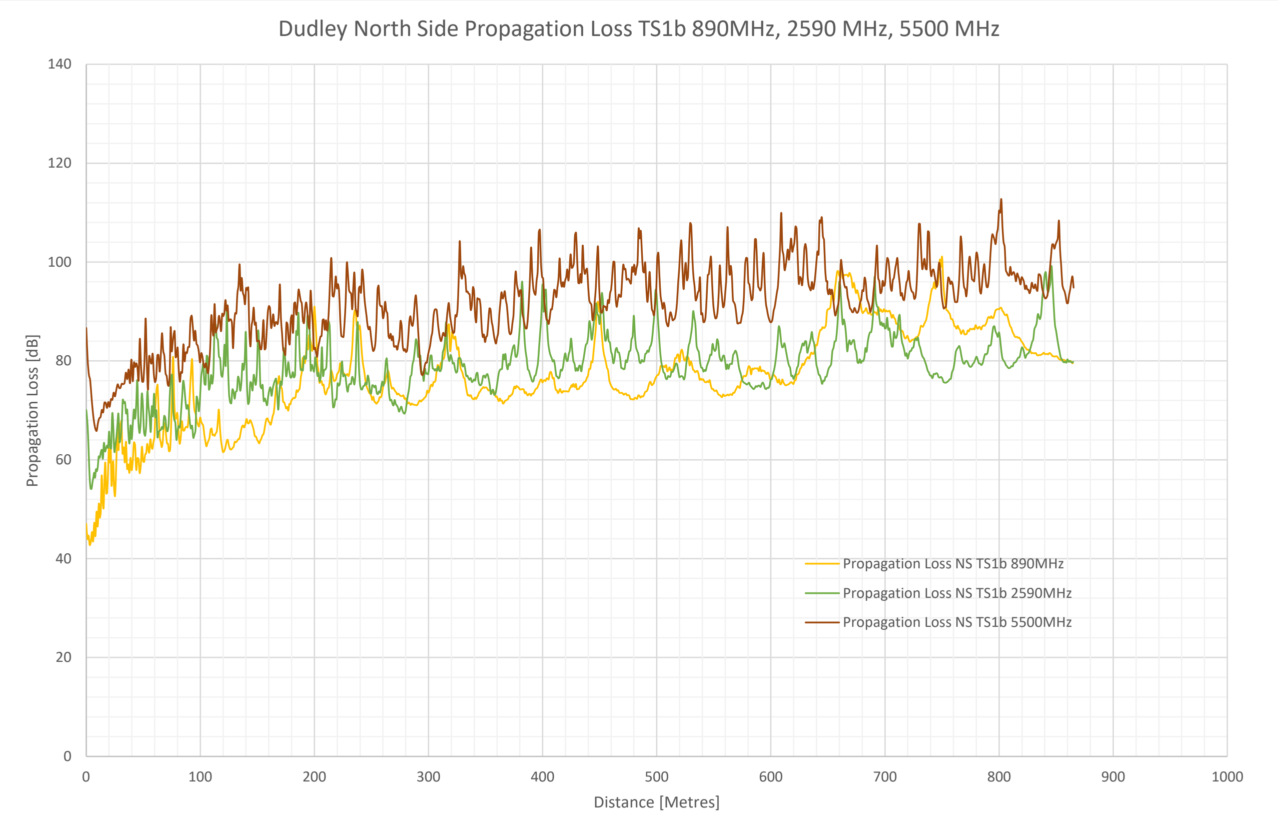


Figure 50 - [TS1b] Signal Propagation: Dudley (North-Curved) At Portal solution (direct connectivity) up to 6 GHz

Standedge (Old) Curved

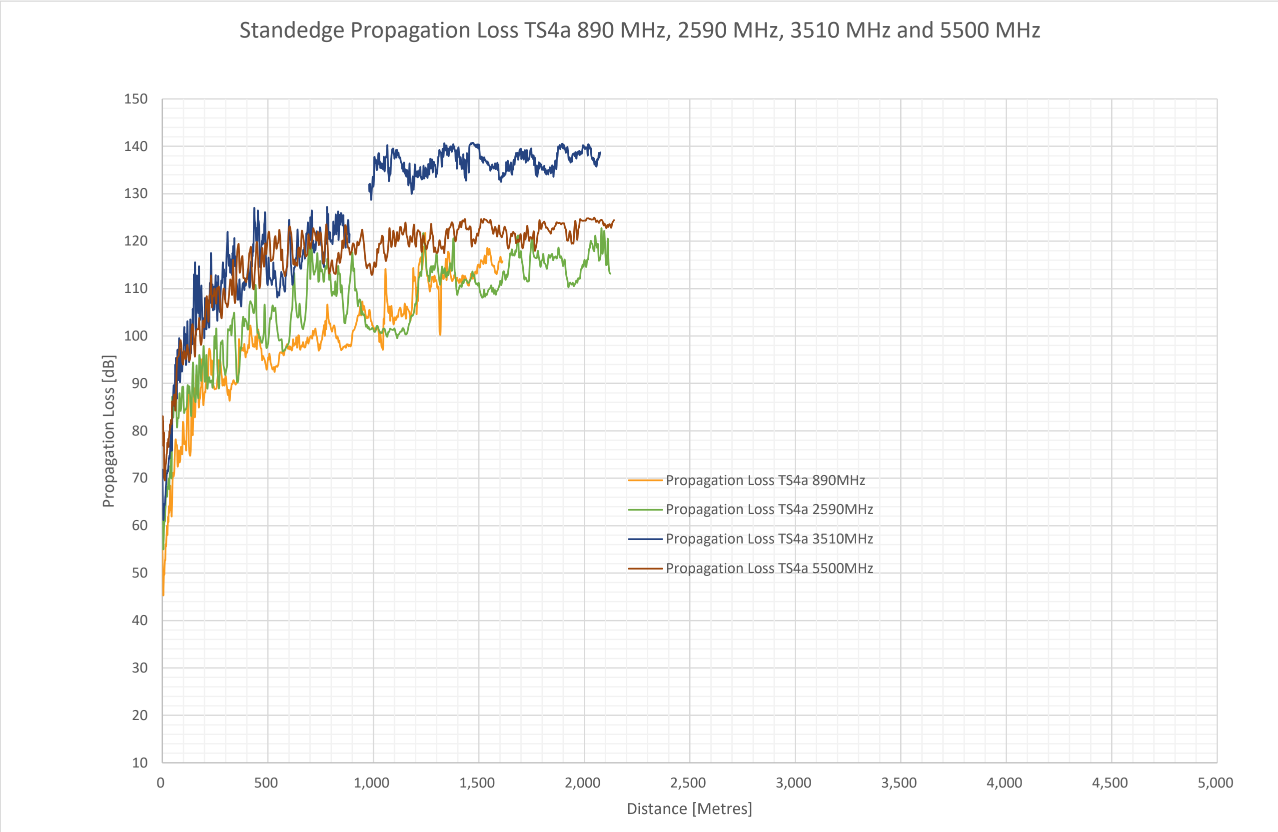


Figure 51 - [TS4a] Signal Propagation: Standedge (Old) Near Portal solution (external train antenna) up to 6GHz

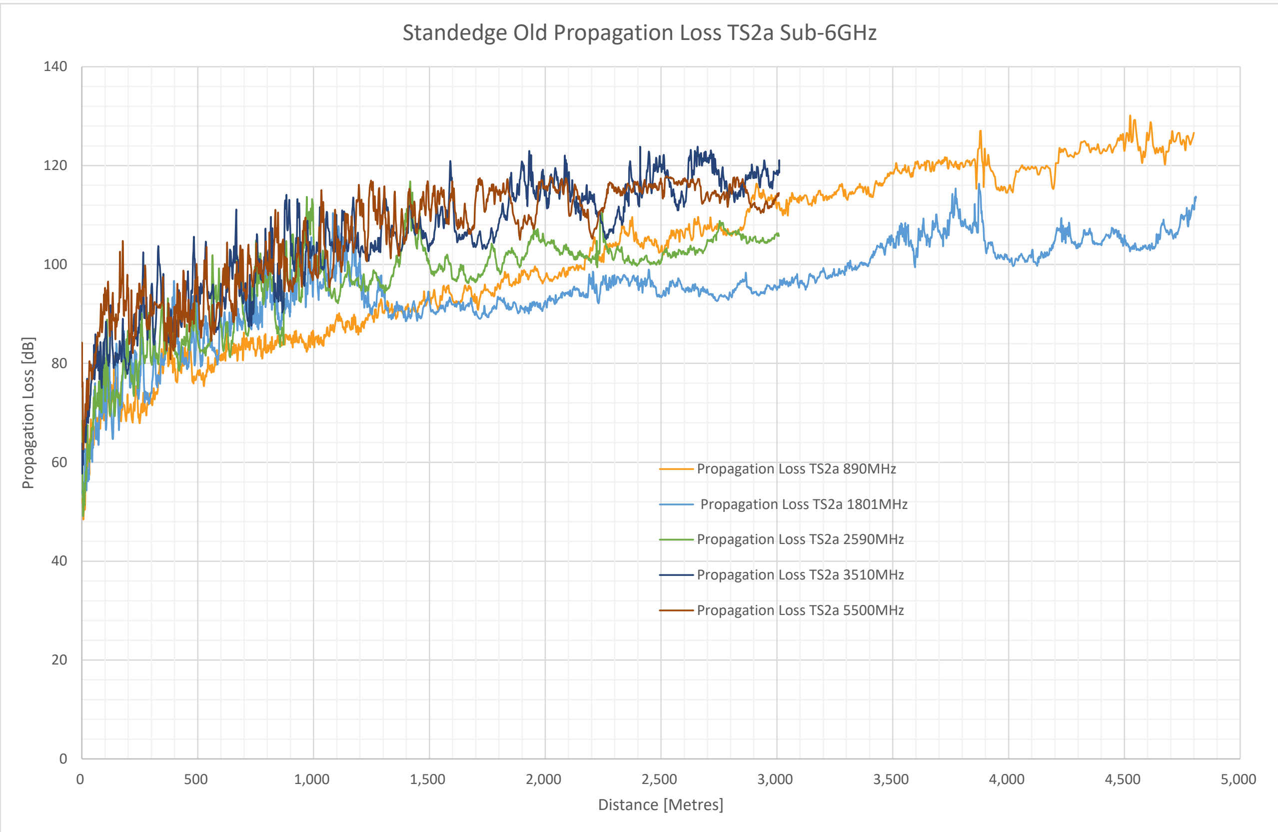


Figure 52 - [TS2a] Signal Propagation: Standedge (Old) At Portal solution (external train antenna) up to 6GHz

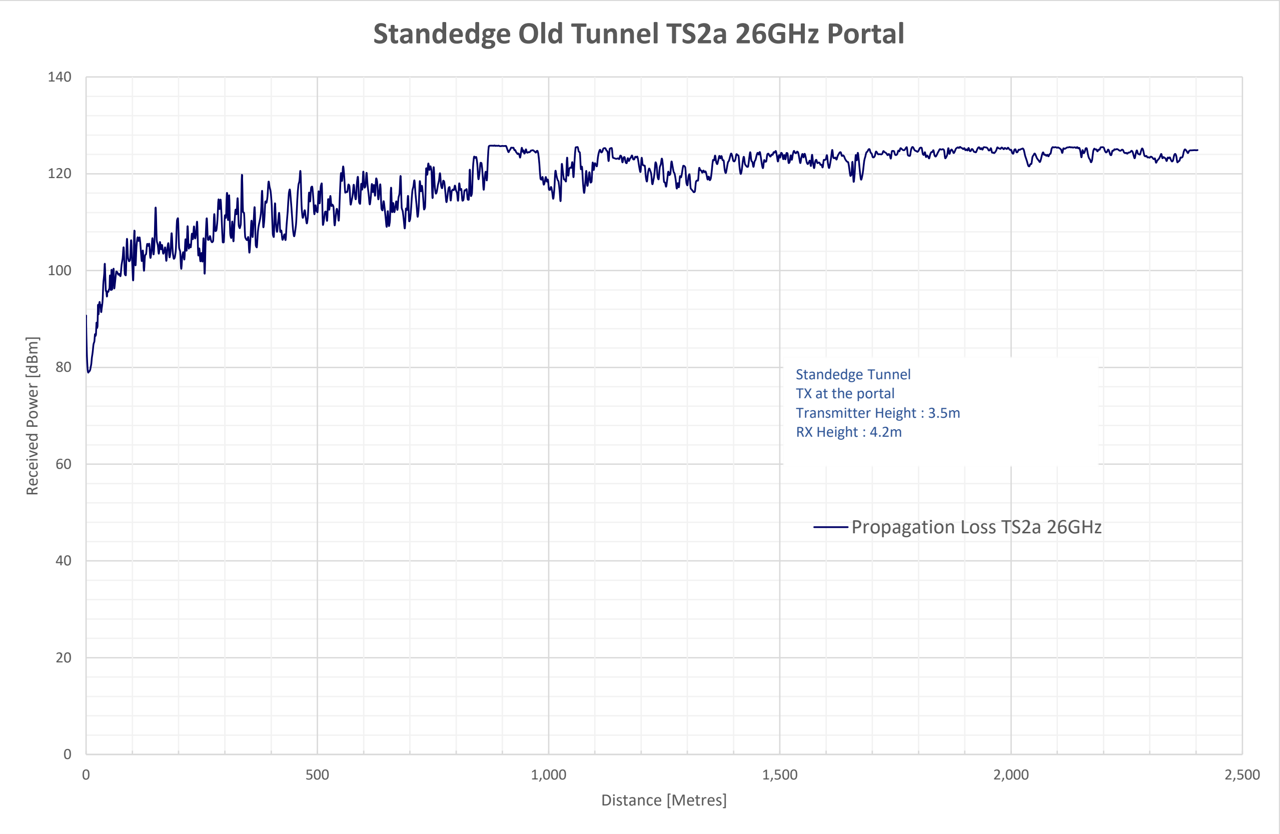


Figure 53 - [TS2a] Signal Propagation: Standedge (Old) At Portal solution (external train antenna) 26GHz

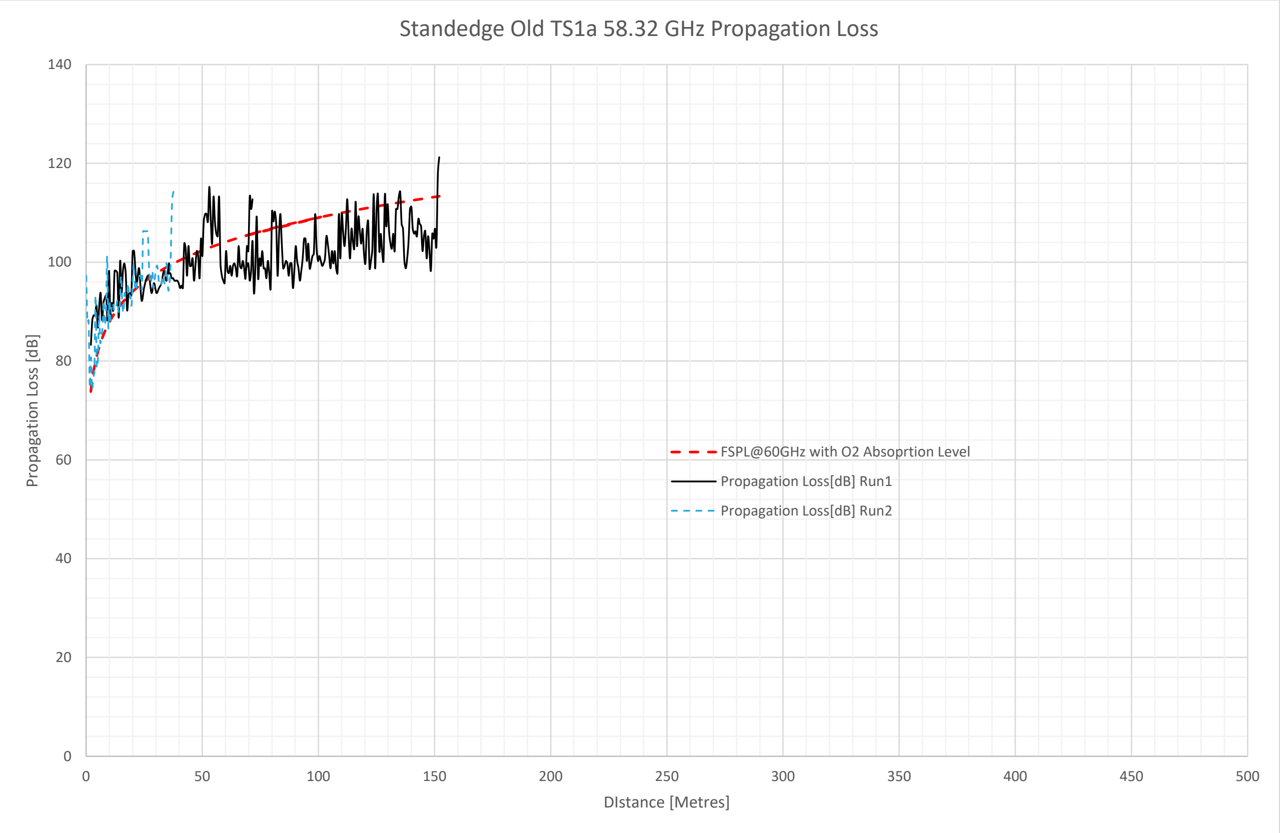


Figure 54 - [TS1a] Signal Propagation: Standedge (Old) At Portal solution (external train antenna) 58.32GHz

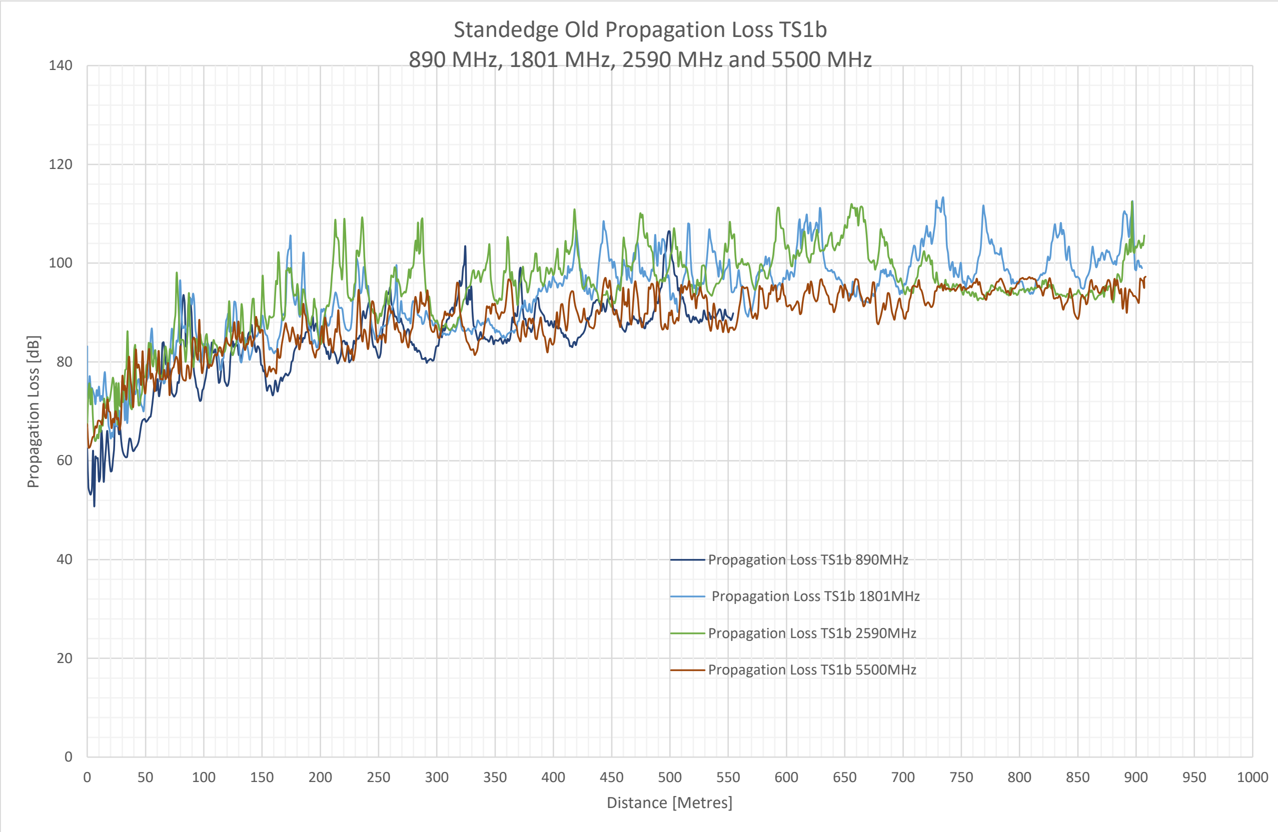


Figure 55 - [TS1b] Signal Propagation: Standedge (Old) At Portal (direct connectivity to passenger device) up to 6 GHz

Copenhagen

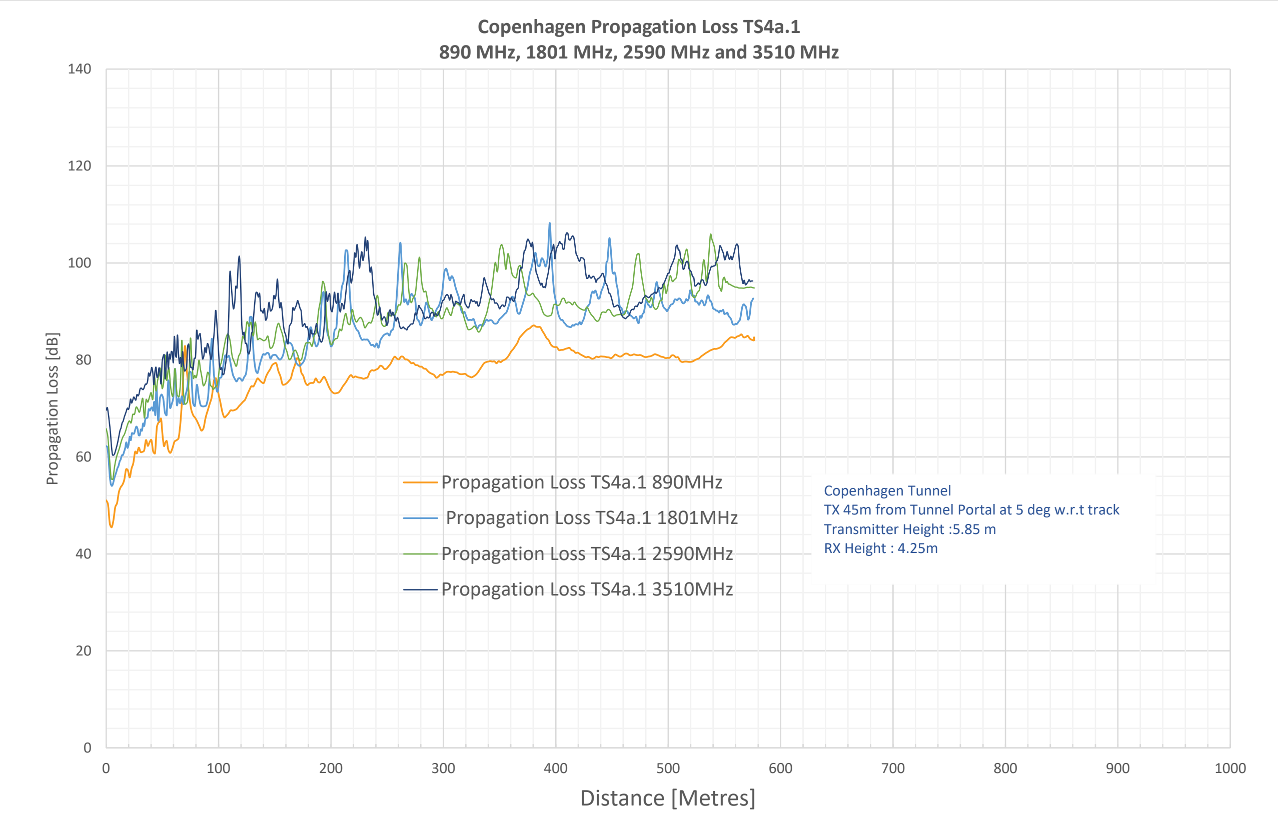


Figure 56 - [TS4a1] Signal Propagation: Copenhagen Near Portal solution (direct connectivity to passenger device) up to 3.5GHz

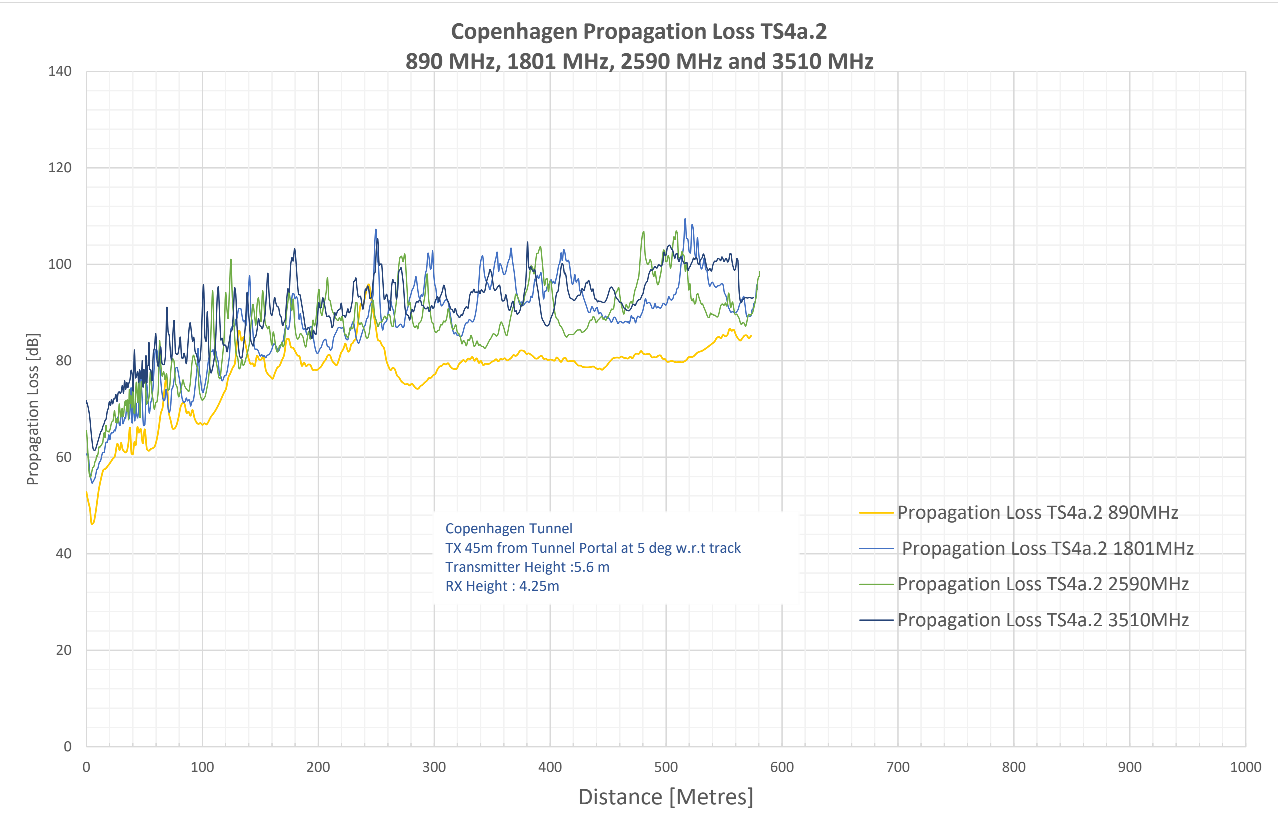


Figure 57 - [TS4a2] Signal Propagation: Copenhagen Near Portal solution (direct connectivity to passenger device), lower side transmitter, up to 3.5GHz

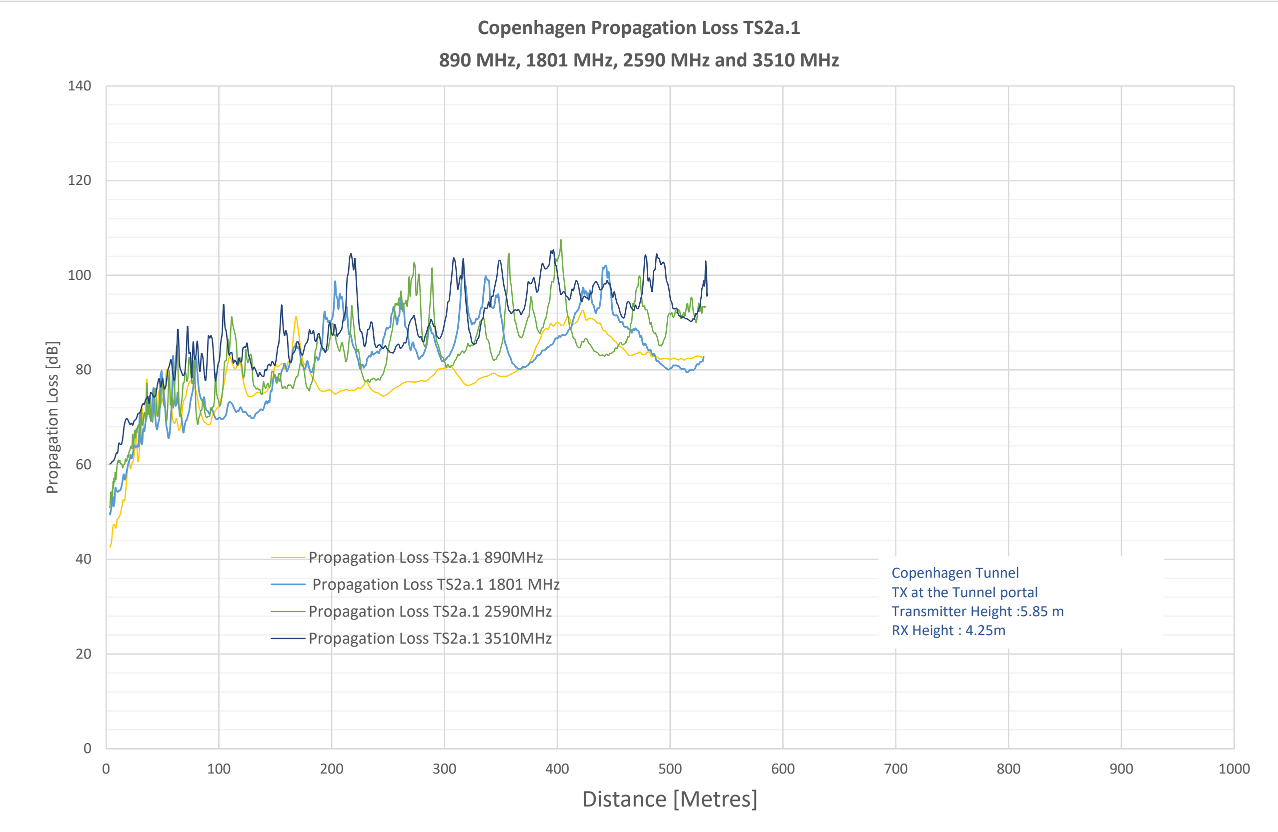


Figure 58 - [TS4a1] Signal Propagation: Copenhagen At Portal solution (direct connectivity to passenger device), transmitter height 5.85m, up to 3.5GHz

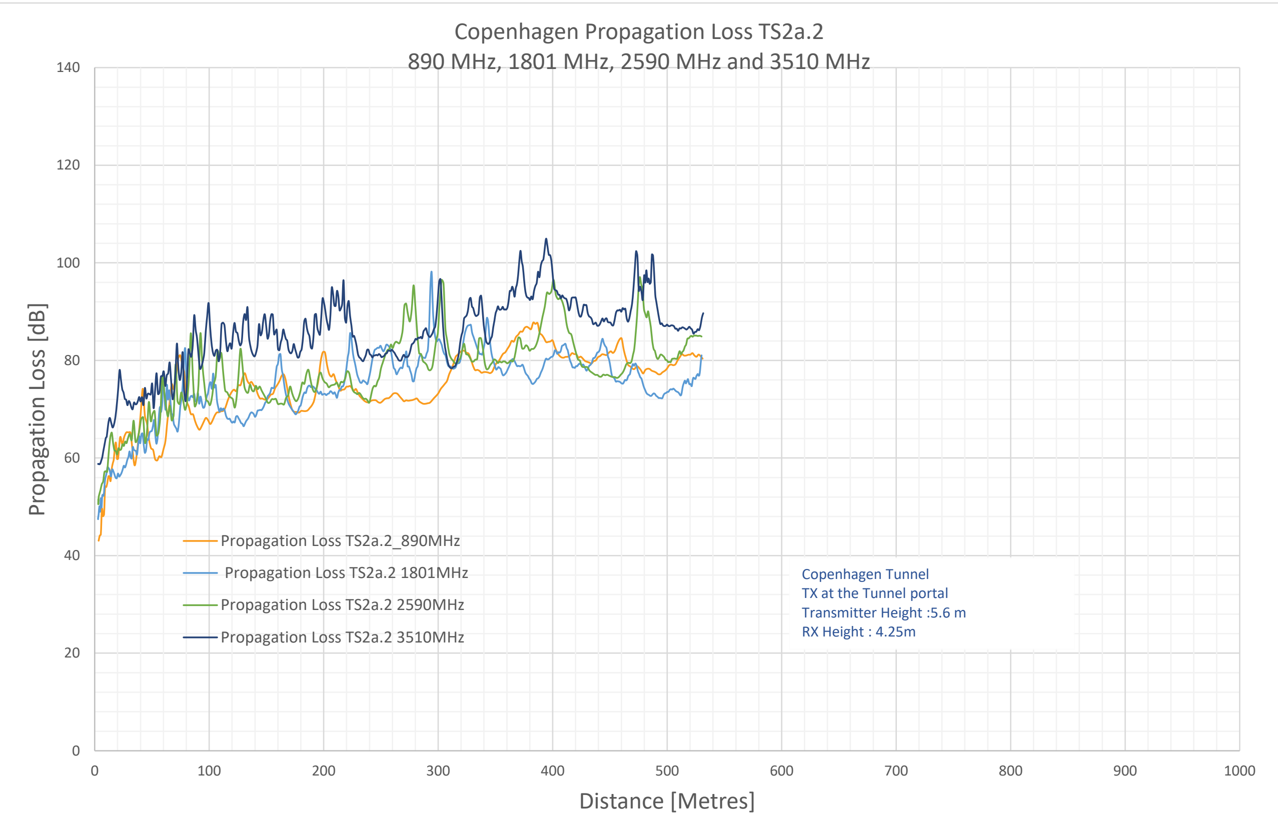


Figure 59 - [TS422a.1] Signal Propagation: Copenhagen At Portal solution (direct connectivity to passenger device), transmitter height 5.6m, up to 3.5GHz

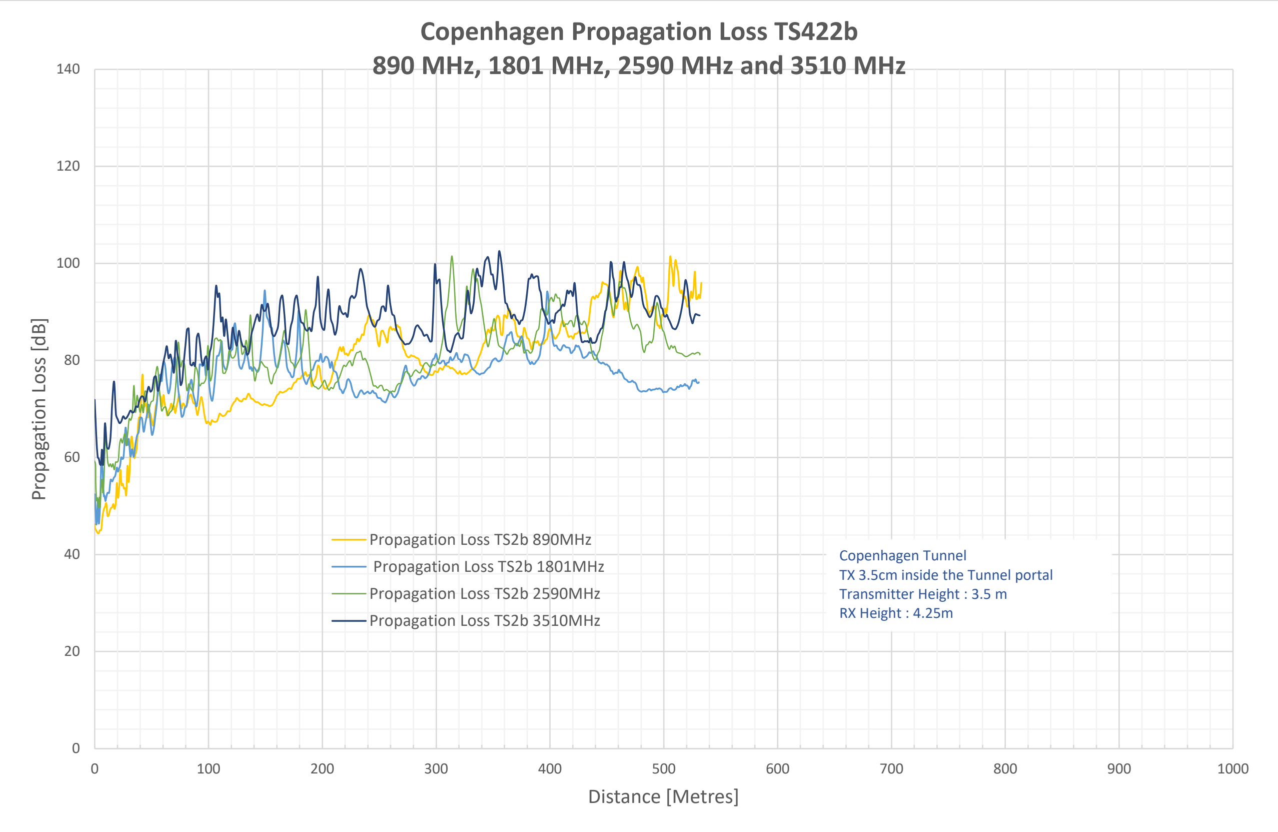


Figure 60 - [TS422b.2] Signal Propagation: Copenhagen transmitter height 3.5m & 3.5m inside Outer Portal at side, up to 3.5GHz

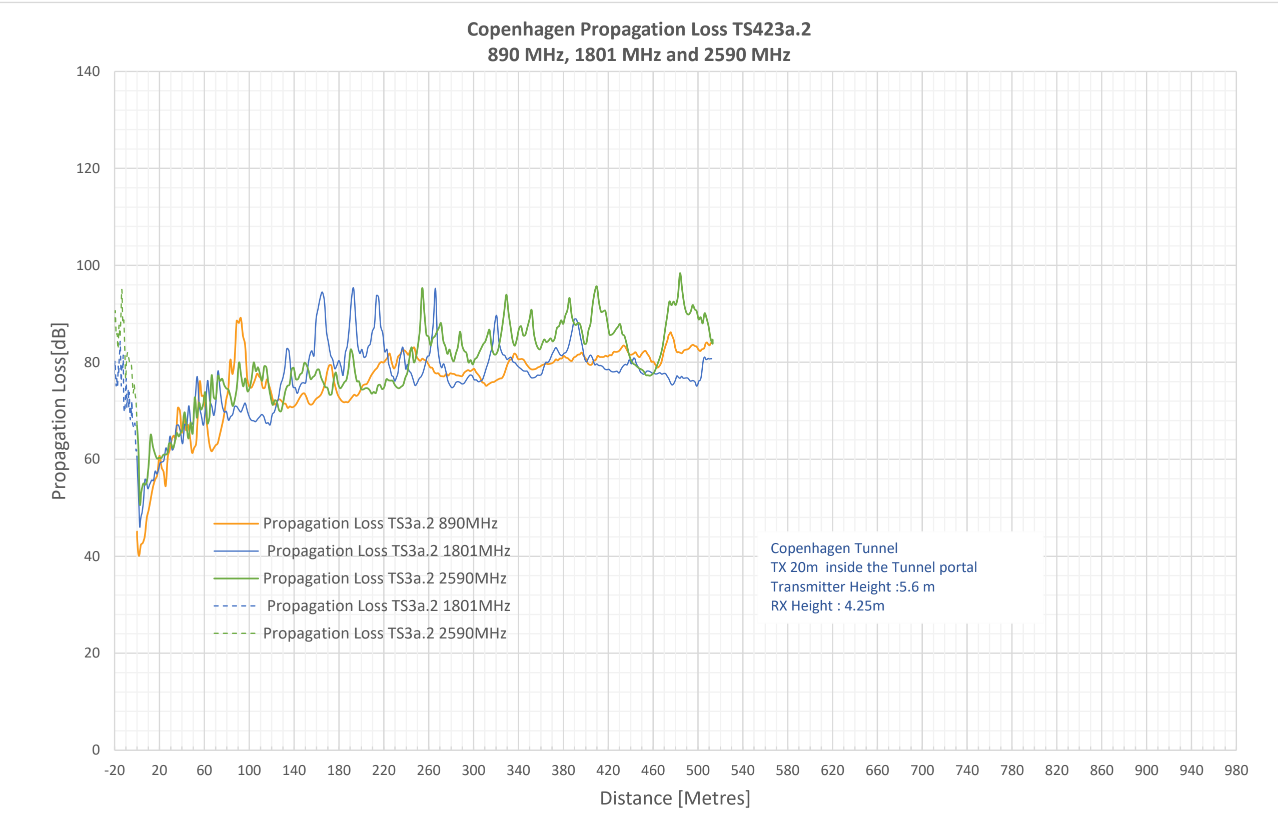


Figure 61 - [TS423a.1] Signal Propagation: Copenhagen transmitter height 5.6m & 20m inside Outer Portal, up to 3.5GHz

App4.4 Practical issues and lessons learned from RF Testing

Table 51 summarises some of the challenges of RF testing at disused tunnels.

Description	Issues
Lack of calibrated test equipment for rental at newly emerging frequencies (60 GHz)	Not readily available for standard equipment rental. The study team improvised by using signal level monitoring built into proprietary mesh network node components (CCSL Met 60G mesh transmitting to CPE).
Factors driving productivity	• Frequency changeover time to swap antennas and cabling. • Need for very careful initial manual alignment for measurements at 60GHz. • Protection of test equipment during inclement weather (February to March 2021) to keep it dry. • Time to complete measurement sweep limited by operating speed: walking pace or realistic vehicle-speed over uneven ground.
Restrictions on tunnel access	• Confirm access has been agreed by all owners of any site. • Access is only possible while full H&S cover is provided, and this may not be flexible. • Access to staff welfare facilities. • Quality of working environment.
Challenges specific to:	
Dudley tunnel	• Operated as a construction site with standard operating hours. • Power and lighting available but 30-minute round trip for comfort breaks.
Standedge (Old) tunnel	• Harsh working environment (deep tunnel, no power or lighting and wet and uneven pot-holed track bed). • One test day disrupted by access clash with the co-owner (Canal & River Trust).
Copenhagen (Eastern Bore) tunnel	• Temporary access to construction site obstructed by yellow plant, road vehicles and material left behind by other contractors. • Presence of unexpected metal fencing along the full length of the tunnel.

Table 461 - Factors affecting test productivity

Endnotes:

i [4] 'Keeping connected: passengers' experience of internet connectivity on Great Britain's railways', Transport Focus, July 2020 https://www.transportfocus.org.uk/publication/keeping-connected-passengers-experience-of-internet-connectivity-on-great-britains-railways/ and [5]'Passenger experience of connectivity on GB's railways', Umlaut (commissioned by Transport Focus), June 2020, https://d3cez36w5wymxj.cloudfront.net/wp-content/uploads/2020/07/23180037/Passenger-experience-of-connectivity-on-GB%E2%80%99s-railways.pdf

ii Formerly Kathrein

iii This would be true for a usable signal propagation range **r** of ~410m based on Equation [9-1]

iv In a larger core multimode or plastic fibre, the modal nature of propagation only become visible when a coherent and polarised source such as a laser. Light from the out of a fibre projected onto a screen in a dark room reveals dancing speckles of light showing mixing and interference of the many modes of light being propagated.

v Label not actually marked on chart.