ARUP ALLIANCE

Department for Transport

Mobile Connectivity in rolling stock – radio frequency attenuation characteristics

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Rail Digital Services – Signal Attenuation

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LS telcom and ARTE Labs planned and carried out the field work and radio frequency field testing to assess Vehicle Penetration Loss and signal attenuation within train carriages and contributed to the literature review.

Executive Summary

This study is part of the Department for Transport's objective to understand the practical and technical barriers to improving connectivity on the railway. Research by Transport Focus continues to report[i] that while mobile connectivity for some can be good, it remains poor for many rail passengers. Rail passengers currently prefer direct access to their chosen mobile service provider even when train-borne wifi is available.

The aim of the study is to investigate the contribution of passenger rail carriage design to radio frequency (RF) propagation as part of the wider mobile network and to understand important attributes that could influence future train specification and design.

Scope
The scope of the study was technical, and the aim was to gain insights through a combination of literature review, RF field testing of GB mainline rail carriages, and predictive modelling. The focus was train signal attenuation and factors considered included:

- **Rail carriage design** Vehicle Penetration Loss testing was conducted on five vehicles: GWR British Rail High Speed Train Mk III trailer, C2C Bombardier Class 357 Electrostar, SWR Siemens Class 450 Desiro, SWR Siemens Class 707 Desiro City, C2C/ Anglia Bombardier Class 720 Aventra, and design comparisons were made with rail carriages from other manufacturers, especially for rolling stock in service for less than 25 years

- **Technology generation and frequency allocation** for both voice and data services using 2G (GSM), 3G (UMTS), 4G (LTE), and 5G (NR) mobile networks at spot frequencies of 702.5 MHz, 945 MHz, 1,801 MHz, 2,395 MHz, 3,500 MHz and 5,500 MHz

- **Angle of arrival of signals** varying between a signal coming directly towards the side of the train (90° to the line of route) and a trackside transceiver serving the line of route (5°)

- **Passenger location within the train** to explore the effect of external windows, doors and carriage body, and internal fixtures and fittings, on the passenger experience

- **User and Crowding Body Loss** that compounds the effect of Vehicle Penetration Loss, investigated through literature review and the experience of the study team

The study's primary focus was direct connectivity between a mobile network operator's base station transceiver antenna and the built-in antenna within an individual rail passenger's mobile electronic device. However, some assessment was made of propagation within a rail carriage serviced by a ceiling-mounted wifi access point.

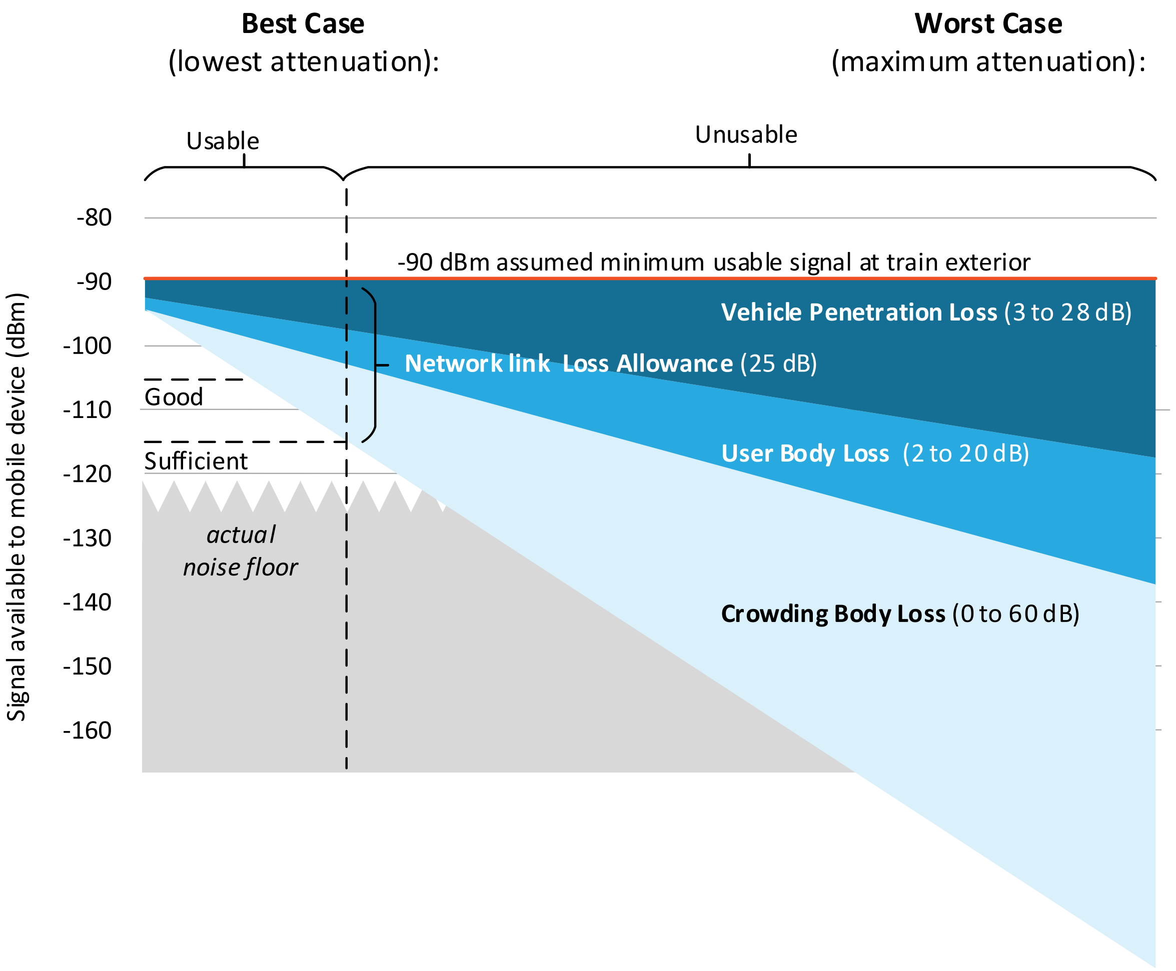
How rail carriage design contributes to a poor mobile connectivity experience for passengers
Direct mobile connectivity is a technical challenge for railways because of the very large range of signal attenuation that can be experienced, ranging from excellent connectivity to no connectivity at all, based on low external signal level, and far beyond the 25decibel (dB) Vehicle Penetration Loss allowance typically made by mobile network operators. The 25dB allowance might otherwise be considered generous, since only 7-10dB is allowed for brick-built residential dwellings and cars.

The figure below highlights the compounding effect on the total mobile operator signal losses between the outside of the train and the passenger's mobile device:

- **Vehicle Penetration Loss** (3 to 28 dB) attributed to the train design

- **User Body Loss** (2 to 20 dB) related to how the passenger holds and uses their mobile device

- **Crowding Body Loss** (ranging from 0dB to higher than 60dB under extreme crowding) caused by signal absorption by the bodies and belongings of other passengers



How the wide range of train signal attenuation affects direct mobile connectivity

This wide range of signal loss (from 5dB to upwards of 100dB) contrasts with an assumed baseline mobile operator signal of -90dBm (an absolute power level of 1 picoWatt or 10^{-12} W) along the line of route, with up to 25dB of additional loss to deliver a signal deemed "sufficient" by Ofcom.

With an external signal level of -90dBm and an overall signal attenuation of less than 25dB throughout the train, passengers should experience reasonable connectivity. Any higher attenuation and their experience will be poor. This large range highlights one reason why Transport Focus' research and national passenger rail surveys continue to report a good service for some and none or poor service for others.

User Body Loss is affected by the design of the built-in mobile device antennas and can vary by up to 10dB. Train designers can do little to reduce crowding or how passengers hold and use their mobile devices other than to influence where they sit, stand or perch while travelling.

This leaves Vehicle Penetration Loss linked to the design and construction of the rail carriage as an important consideration particularly for new rolling stock designs. The table below shows the range of Vehicle Penetration Loss measured during the study on four rail carriages (3dB to 28dB overall) alongside the area of bodyside window glazing per rail carriage side.

Rail Carriage	**Measured Vehicle Penetration Loss* (dB)**	**Approximate Area of Bodyside window glazing (m^2 per carriage side)**
British Rail HST Mk III Trailer (1975)	3 to 19	9-10
Bombardier Class 357 Electrostar (2000)	3 to 18	11-12
Siemens Class 450 Blue Desiro (2003)	7 to 28	11-12
Siemens Class 707 Desiro City (2017)	7 to 25	11-12
Overall	***3 to 28***	

*through window, door or metal at all measured frequencies, angles of arrival and passenger locations

Range of Vehicle Penetration Loss measurements

Vehicle Penetration Loss levels as low as 3dB to 7dB can be experienced at window seats thanks to large areas of plain glass bodyside window glazing. However, glazing is not the only factor at work for those parts of the rail carriage experiencing the highest levels of Vehicle Penetration Loss. Despite having the same window and door layouts as the Bombardier Electrostar, and more glass than the BR Mk III trailer, the two Siemens Desiros experience losses that are 6dB to 10dB worse. There appears to be two possible reasons. The first is that the continuously welded aluminium car bodies of the Desiros screen out more RF through ‘Faraday cage’ effects compared with the more complex huck-bolted assembly of the (also) aluminium Electrostar and the lower conductivity steel Mk III trailer. The second reason is that the Desiro was designed to higher thermal and acoustic insulation standards leading to tighter physical tolerances and improved sealing at windows and doors reducing RF propagation.

Train design choices are constrained by many competing commercial, operational, engineering, safety and environmental requirements. Suppliers of recent GB fleets, Hitachi, CAF and Stadler, have all favoured strong, light weight, welded aluminium car bodies that may be expected to have similar RF propagation characteristics to the Siemens Desiro given similar areas and types of bodyside glazing.

When bodyside glazing area is considered, the range of Vehicle Penetration Loss across the national fleet may be even greater. Fleets such as the Hitachi AT300 Class 801/ Class 802 fleets have lower levels of glazing (6-7 m^2 per carriage side). The GWR and East Coast Class 801/ 802s have less glazing than the Avanti West Coast Alstom Class 390 Pendolino (7-8 m^2 per carriage side) that has been notorious for poor direct mobile connectivity since it was introduced in 2002.

The importance of rail carriage bodyside windows and glazing to future Vehicle Penetration Loss performance

Train specifiers must continue to specify direct mobile connectivity through the control of Vehicle Penetration Loss, by setting minimum areas of bodyside glazing and minimum RF propagation characteristics for glazing materials taking into account wider environmental considerations.

Whilst, plain (toughened or laminated) glass is best for RF propagation, stricter environmental sustainability standards mean there is a need to improve thermal insulation in the winter to reduce radiant heat loss, and reduce solar gain during the summer to improve the efficiency of air conditioning, through specifying low emissivity glass.

Such glass, coated with a continuous metallic layer, is an excellent reflector of infrared radiation and is able to block both incoming solar radiation and outgoing radiated lost heat, but, as the experience of European railway operators has found, it also blocks mobile signals increasing Vehicle Penetration Loss by 20-30dB. To address this, one technical workaround has been to break up the metallic layer by removing 2.5% of the surface area in a specific pattern to retain most of the thermal performance and allow through most of the RF signal.

Other options

The application of new composite materials to rail carriage design may promise reduced Vehicle Penetration Loss in the longer term, but not if sandwiched with aluminium foil to reflect radiant heat and act as a water barrier, or if made of another electrically conducting material such as carbon fibre.

The findings of this study also reinforce those of the ‘Not Spots’ report by Mott Macdonald for Ofcom in 2012[ii] that recommended: infrastructure investment to deliver consistent signal strength along the line of route including rural areas, deep cuttings and tunnels, raising the signal strength by 30-35 dB to cancel out the Vehicle Penetration Loss, avoidance of solid metallic coatings or films on bodyside windows, and to sidestep Vehicle Penetration Loss and Crowding Body Loss with train-based gateways to relay signal between network and passenger using external train antennas.

As an operational workaround on existing fleets, train operators could inform passengers where to find best connectivity on the train and along the line of route and make them aware of progressive improvements as they become available.

If the long-term aim is to offer every rail passenger a ‘good’ mobile connection, then work needs to be undertaken to minimise signal attenuation between network base stations and passenger mobile devices through consideration of the end-to-end link. This includes improving the external signal strength and through the use of ‘technology-agnostic’ train-borne gateways (such as Digital On-board Repeaters or small-cells) to re-radiate such signals internally to significantly reduce, or eliminate, the effect of Vehicle Penetration Losses.

* * *

This study has found that the design of railway carriages can have a significant effect on direct mobile connectivity because of the wide range of signal attenuation that can be experienced, especially on crowded trains (ranging from 5dB to conceivably in excess of 100dB).

There is limited opportunity to improve current train design to reduce the Vehicle Penetration Loss component due to the technical requirements (a typical range of 3 to 28dB based on selected measurements and even worse on some fleets), but steps can be taken to minimise such losses in future procurements.

In future rail carriage procurement, the Department for Transport should ensure that environmental standards are balanced with the need to minimise Vehicle Penetration Loss, to provide rail passengers a satisfactory rate of mobile connectivity whilst travelling. The challenge remains of inconsistent signal coverage across the GB rail network but there is a great opportunity to encourage the development of ‘technology agnostic’ train-borne gateways able to take advantage of new capacity as it evolves and improve the experience of travelling for rail passengers.

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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], reinforced 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 millimetre wave frequencies (60GHz) 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 service provider for 96% data calls compared to train-borne wifi [4,5], this is likely to be linked to uneven coverage along the line of route. This is why the DfT wishes to understand what affects the signal level that reaches passengers' mobile devices, especially as the signal has to travel through the train from trackside to passengers' mobile devices. This is partly Vehicle Penetration Loss (VPL) caused by the design and construction of the train itself and partly by the presence of passengers and how they use their mobile devices.

The DfT also wishes to understand the factors affecting the propagation of signal between train-borne 'gateway devices' distributing signal and serving data to passenger devices throughout the carriage and train.

1.2 Purpose

The aim of this study is to investigate the contribution of passenger rail carriage design to radio frequency (RF) propagation as part of the wider mobile network and to understand the principal attributes that could influence future train specification and design.

1.3 Audience and Stakeholders

This report is expected to be of interest to the DfT, the Department for Digital, Culture, Media and Sport (DCMS), Network Rail, the NIC, Ofcom, Transport Focus, Rolling Stock Operating Companies (ROSCOs), Rail Delivery Group (RDG), Train Operating Companies (TOCs), and the current and future supply chain.

The study acknowledges the willingness of fleet owners, owning groups, operators and maintainers to make trains available for test and patiently facilitating the test sessions. This was especially taxing for all involved as the field tests kicked off in early Spring 2020, just as the Covid-19 pandemic struck. As a result, a more limited selection of trains was eventually tested between lockdowns by Autumn 2020.

1.4 Scope

The scope of the study is technical, to gain insights through a combination of literature review and radio frequency (RF) field testing of GB mainline rail carriages supported by predictive modelling. The focus was train signal attenuation and factors considered included:

- **Train design** where testing was conducted on five vehicles: GWR British Rail HST Mk III trailer, C2C Bombardier Class 357 Electrostar, SWR Siemens Class 450 Desiro, SWR Siemens Class 707 Desiro City, C2C/ Anglia Bombardier Class 720 Aventra, and design comparisons were made with rail carriages from other manufacturers, especially for rolling stock that has been in service for less than 25 years
- **Technology generation and frequency allocation** for both voice and data services using 2G (GSM), 3G (UMTS), 4G (LTE), and 5G (NR) mobile networks at spot frequencies of 702.5 MHz, 945 MHz, 1,801 MHz, 2,395 MHz, 3,500 MHz and 5,500 MHz
- **Angle of arrival of signals** from signal coming directly at the side of the train (90° to the line of route) to a trackside transceiver serving the line of route (5°)
- **Passenger location within the train** to explore the effect of external windows, doors and carriage body, and internal fixtures and fittings on the passenger experience
- **User and Crowding Body Loss** that compounds the effect of Vehicle Penetration Loss, investigated through literature review and the experience of the study team

The main focus was direct connectivity between a mobile network operator's base station transceiver antenna and the built-in antenna within an individual rail passenger's mobile electronic device. However, some assessment was made of propagation within a rail carriage serviced by a ceiling-mounted wifi access point.

2 Mobile Connectivity for Rail Passengers on Trains

This section outlines the range of mobile services offered directly by Mobile Network Operators (MNO) to rail passengers as part of their overall network provision. It explains the technical provision of signal coverage to the track and typical allowances for further attenuation of the signal as it passes into the rail carriage to reach the built-in antennas of passenger mobile devices. Although the focus of this study is on direct connectivity, it also outlines the use of train-borne 'gateway' nodes with external train-top antennas to relay a trainload of traffic between passenger devices and land-based transceiver nodes.

2.1 Demand for mobile connectivity on trains

Rail passengers expect to be able to enjoy the full benefits of mobile connectivity from their MNO when travelling on trains as anywhere else. The mobile operator normally takes the lead in forecasting and measuring demand subject to regulation by Ofcom and plans its cell network accordingly which may include coverage of railway lines.

The aim of this study is to understand how trains and their interior designs, coupled with passengers and their belongings affect the level of signal attenuation between the external signal levels and the signal that reaches the built-in antennas of passenger mobile devices. This signal attenuation forms part of the overall RF link budget between the MNO's base station and each passenger's mobile device. 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. Similar criteria also apply for indirect proprietary RF links carrying traffic between a land-based base station and a 'gateway' node on the train providing onwards connectivity to passengers' mobile devices. For example, this could be based on MNO coverage, external wifi or millimetric wave solutions.

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 has monitored passenger traffic levels (Table 1).

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 90s voice calls uninterrupted during journey.
2017	wifi (Ofcom)	0.15	120	800 active users per train [6]
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 2Mbps consistent data rate per pax to browse/ view mobile video.[4]
2025	3G/4G data (Ofcom)	1.5	1,200	Tenfold increase 2017-25 [6]

Table 1 Forecast traffic demand trends for train-borne mobile connectivity

Table 1 suggests that near term RF link budget planning needs to target at least 1Mbps per passenger device directly and 1.2Gbps to the whole train through wifi or other train-borne gateways.

2.2 Typical capacity of mobile connectivity technologies

The theoretical information carrying capacity of a wireless signal is proportional to the signal level and bandwidth made available. The actual data capacity that can be achieved depends on many additional factors: sifting information from noise (thermal) and distortion/ interference (such as in-band, doppler shift, multi-path fading), switching capacity constantly between different users and traffic types on a commercial basis, encryption to aid security and improve coding efficiency, and new techniques such as carrier aggregation and Multiple Input Multiple Output (MIMO) antennas to increase available user capacity.

Modern mobile digital telecommunications systems evolve through generations of standards to take advantage of new frequency spectrum, increased processing power that unlocks innovation in coding and transmission protocols to approach ever closer to the theoretical limits.

The mobile connectivity generations of 2G (GSM), 3G (UMTS), 4G (LTE) and 5G (NR) and in parallel, wifi generations (IEEE802.11 et al.) have become increasingly complex. However, the fundamentals still apply. Ultimately it is a trade-off between the desired quality of service (voice quality or data capacity), signal power level and overall signal bandwidth.

Figure 1 shows how theoretical single channel data capacity (Million bits per second, Mbps) varies with signal power for several different 4G/ 5G configurations and signal bandwidth. The configurations represent different 4G/5G design choices (Appendix 2.1):

- 4G or 5G
- Channel bandwidth allocated (5, 10, 20, or 40 MHz)
- Antenna design – 2 x 2 Multiple Input Multiple Output (MIMO) designs to increase the spectral efficiency
- Proportion of capacity allocated to downlink or uplink traffic (in a Time Division Duplex (TDD) system)
- Time or Frequency Division Duplex (alternative options for two-way communication)

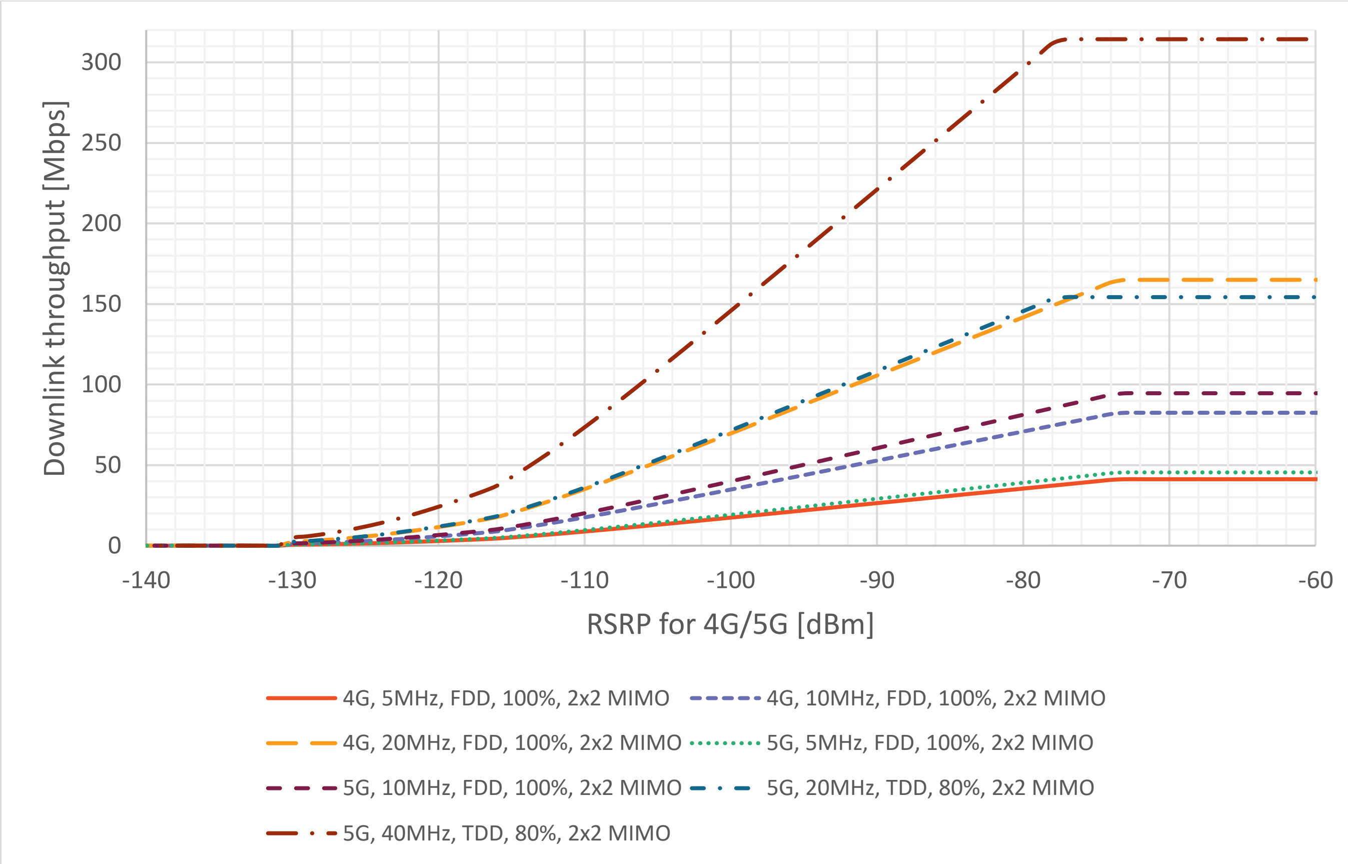


Figure 1 Achievable throughput values based on signal level, technology and channel bandwidth.

The signal power level is measured in units of dBm.

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, +10dB means 10 times greater, +20dB 100 times greater and so on. -10dB means a signal 1/10th of the reference signal, -20dB 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, -6dB ¼ or 25%.

So, a range of signal attenuation between -3dB and -30dB is actually a wide range from ½ (50%) of the reference signal down to 1/1000th (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 = 0dBm, then 0.1mW = 1mW/10 = 0dBm – 10dB = -10dBm.
Also, signal strength tends to decrease steadily but non-linearly from a point source. On dB v linear range plots the attenuation can be characterised as a straight line with the slope showing the steady rate of reduction in dB/km. For example, -10dB/km represents a signal decaying inversely with range and -20dB/km a signal decaying inversely with the square of range.

Mobile signals are delivered using a network of land-based base stations using antennas mounted at height, either on purpose-built masts or existing structures. Since signal diminishes with distance from the transceiver antenna, the smaller the signal that passenger mobile devices can work with, the greater the range of any one transceiver and the cheaper the coverage costs since fewer transceivers are required. The balance of signal strength and channel capacity is determined by MNOs' network configuration but subject to regulation. Ofcom commissions regular surveys and sets a range of recommended minimum signal power levels for different services [6-8]. This is not an exact science and other countries choose different targets [9].

Table 2 shows recent minimum (external) signal level thresholds assumed by Ofcom in recent surveys [7].

Traffic	Technology	Signal power metric	Outdoors (dBm)	Indoors and in-car (dBm)
Voice	2G	RxLev	- 81	- 71
Voice	3G	RSCP CPiCH	-100	- 90
Voice	4G	RSRP	-105	- 95
Data (basic)	3G	RSCP CPiCH	-100	- 90
Data (basic)	4G	RSRP	-115	-105
Data (enhanced)	4G	RSRP	-105	- 95

Table 2 General mobile signal strength thresholds
Source: Ofcom 2020 [7]

Note that progressive evolutions of technology have refined how signal level is measured from basic received signal level (RXLev) for 2G to Received Signal Code Power of the Code Pilot Channel (RSPC CPiCH) for 3G to Reference Signal Received Power (RSRP) for 4G/ 5G which are directly relevant to cell handover and decoding of the embedded data. This difference in signal measurement definition and practice is why 2G signal strength indicator requirement appears to be much higher than 3G/ 4G/ 5G, typically 20dB more.

Target signal levels assume the equipment is being used outside. However, Ofcom also makes provision for up to 10 dB signal attenuation into the average brick-built residential dwellings and for cars [10, 11].

For railway passengers, mobile operators have typically assumed up to 25dB loss between the outside of the train and the built-in antenna on the passenger's mobile device. This means a trackside signal of least -90dBm should still deliver at least -115dBm to the passenger's mobile device for a reasonable quality of service. Sections 4 to 6 examine if this assumption bears scrutiny.

2.3 Spectrum allocation

Allocation of carrier frequency spectrum is a complex commercial and technical process regulated by Ofcom in Great Britain (GB). Table 3 presents an overview of spectrum available to mobile network operators by generation of mobile technology. Some spectrum is already being 're-farmed' as mobile operators wish to migrate use of their signal allocation from 2G to 4G services, for example at 1,800 MHz.

The bandwidth available for traffic typically increases with spectrum frequency. For modelling purposes, we assumed that 10MHz is typically available up to 1,000 MHz, 20 MHz up until 3,000 MHz, and 40 MHz at 3,800 MHz per MNO in the cellular bands.

Spectrum	2G	3G	4G	5G
700 MHz				Yes (auction 2021)
800 MHz			Yes	
900 MHz	Yes (+GSM-R)	Yes		
1,800-2,100 MHz	Yes	Yes	Yes	
2,300-2,600 MHz			Yes	
3,400-3800 MHz			Yes	Yes (auction 2021)

Table 3 Overview of UK spectrum available for mobile connectivity and its typical application
Source: [12]

RF testing and modelling during this study has tested spot frequencies between 700 MHz and 5,500MHz to cover the conventional 2G (GSM), 3G (UMTS), 4G (LTE) and 5G (NR) and wifi frequencies.

Based on spectrum type and test licences, the following spot frequencies chosen were:

- 702.5 MHz
- 945 MHz
- 1,801 MHz
- 2,395 MHz
- 3,500 MHz
- 5,500 MHz

2.3 Alternative mobile services

Whilst it is possible to deliver far higher data throughputs to trains than that possible using the MNO's conventional 4G and 5G services, such services require the use of additional train-borne signal relays, train roof-top mounted antennas, and dedicated trackside infrastructure. These 'signal relays' convert the external signal and redistribute its capacity to passengers typically using wifi access points fitted in each carriage.

Whilst emerging millimetre wave technologies (>26GHz) are not currently expected to be used for direct network connectivity to passenger devices (that is, transmitted by the MNOs through the carriage walls, windows and doors), they are candidates for dedicated solutions able to carry high capacity traffic through line-of-sight links between the trackside and train.

As noted, for this study, only current and planned MNO low- and mid-band and wifi frequencies were tested in the sub-6GHz bands.

3 Deployment of GB Mainline Rail Fleet

This section provides an overview of the GB mainline fleet and its operational deployment to carry passengers, the selection of train carriages for RF measurement and modelling, and design features relevant to RF propagation. The effect of train design on Vehicle Penetration Loss is discussed further in Section 4.

Impact of Covid-19 Pandemic on this study
This study was originally planned pre-Covid-19 on the basis of continuing steady growth in rail traffic equivalent to 1.8 billion passenger journeys 2018-19 [13] and to test up to 12 train carriages representative of the characteristics of the national fleet.
Testing started on Tuesday 10th March 2020 at GWR's Laira Depot in Plymouth. However, the remainder of the test programme had to be postponed with the announcement of the first national lockdown from 23rd March 2020. A reduced series of tests during August and September were made possible following the partial lifting of restrictions. Four test sessions were completed successfully but a fifth session had to be curtailed because of other factory priorities.

3.1 GB mainline rail fleet and its deployment

The GB national fleet comprises some 12,900 passenger-carrying rail carriages operated by a number of train operators, most franchised by the DfT, and some open access. Since the privatization of British Rail there have been six main suppliers of passenger rail vehicles (Table 4, based on Appendix 1).

Train Supplier	% Rail Vehicles	% Passenger Journeys	Comment
British Rail Engineering Ltd	15	17	All more than 25 years old
Bombardier Transportation	40	36	Recently acquired by Alstom, includes ABB and ADtranz
Siemens	18	22	
Alstom	10	12	Includes Metro-Cammell
Hitachi	10	6	
CAF	5	5	
Stadler	2	2	
TOTAL	***100***	***100***	

Table 4 Suppliers of the current GB passenger fleet

Trains typically have design lives of 25 to 40 years, although these can be extended by refurbishment.

3.2 Selection of train carriages for RF measurement and modelling

The aim of this study was to test as wide a selection of rolling stock as possible with the following characteristics:

- Trains on which most passengers travel
- Train type (long distance versus commuter with different external carriage design and interior layouts)
- Range of design factors linked to RF propagation
- Variety of suppliers and construction techniques
- Different ages to reflect evolving standards
- Trains with a remaining useful life of at least 15 years

The study was also constrained by fleets made available to test. This depended on the active support, commitment and facilitation from fleet suppliers, owners, owner groups, operators and maintainers, and for the trains and depot facilities to be available on the dates planned and agreed with the test team. This was not straightforward as all the fleets were either in active passenger service and committed to tight timetable diagrams and planned maintenance cycles, or to the pressures of an assembly works, and always the risk of a sudden demand for unplanned work.

The trains tested or modelled account for at least half passenger journeys or are similar to those of other fleets and manufacturers. The rail carriages tested were by year of service introduction:

- 1975+ British Rail HST Mark III 125mph 23m trailer carriage
- 2000 Bombardier Class 357 Electrostar 100 mph 4 x 20m Electric Multiple Unit (EMU)
- 2003 Siemens Class 450 Desiro 100 mph 4 x 20m EMU
- 2017 Siemens Class 707 Desiro City 100 mph 5 x 20m EMU
- 2020 Bombardier Class 720 Aventra 100 mph 5 x 24.4m EMU (part-tested)

By Autumn 2020, four of the five rescheduled test sessions had been completed and a limited set of measurements made on the Bombardier Class 720 Aventra.

Additional carriage modelled:

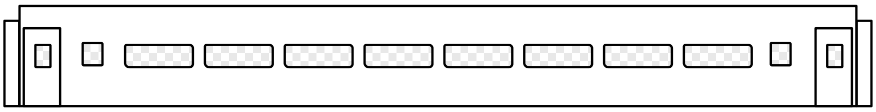
- 2018 Hitachi Class 802 AT300 Super Express 125mph 5 or 9 x 26m bi-mode

Figure 2 overleaf shows the side elevation sketches of all these rail carriages illustrating the main operational and external design features of the car body, bodyside windows and passenger doors.

Figure 2 also includes details of four other rail carriage types that were not tested but are used in Section 4.2 to discuss the implications of test findings on other fleets:

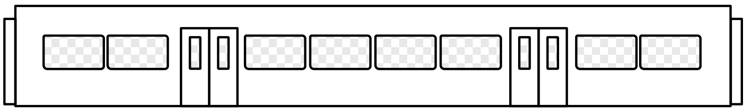
- 2002 Alstom Class 390 Pendolino 140mph tilting train with up to 11 x ~24m carriages
- 2003 Alstom Class 373 Eurostar e300 186mph high speed train with 18 x 18.7m carriages
- 2015 Siemens Class 374 Eurostar e320 200mph high speed train with 16 x 24.2m carriages
- 2011 Hitachi Class 395 AT300 140mph 6 x 20m EMU

The Pendolino was one of the first GB trains to experience mobile connectivity issues and has since been through at least three generations of train-borne gateway devices over the past 18 years, from MNO-specific signal boosters (on-board repeaters, 2006) to a recent upgrade to the capacity and quality of onboard wifi (2018). The Class 373, Class 374 and Class 395 fleets that operate on High Speed 1 were included because of headline evidence available from confidential signal attenuation studies conducted by a mobile operator at St Pancras International Station between 2016 and 2017 [14, 15] (see also Table 12 in Appendix 3).



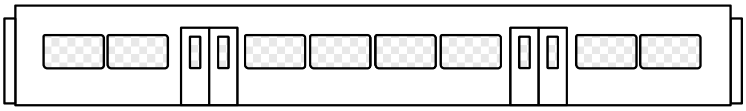
a) **GWR BR HST Mk III** 125mph Trailer, 23m 2+2 seating, end doors (slam)
Windows: toughened glass, 8 main units ~ 1.5m x 0.6m plus two others ~9-10m^2.
Car body: welded steel.

Entered service 1975+
Tested at GWR Laira Depot, Plymouth
Owner: First Group or Angel Trains
Glazing per side 9-10m^2



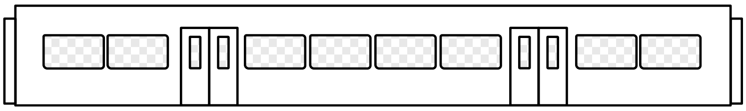
b) **C2C Bombardier Class 357 Electrostar**, 100mph 4 x 20m EMU 2+2 seating,
1.5m door pairs. Windows: toughened glass, 8 main units ~1.6m x ~0.9m ~11-12m^2.
Car body: longitudinal aluminium panels huck-bolted at the ends with Glass Reinforced Plastic (GRP) steel-framed cabs.

Entered service 2000
Tested at C2C East Ham Depot
Owner: Angel Trains
Glazing per side 11-12m^2



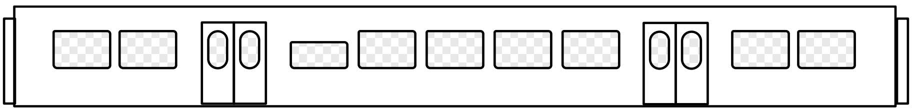
c) **SWR Siemens Class 450 Desiro**, 100mph 4 x 20m EMU 2+3 seating
1.5m door pairs (Carriage side layout appears similar to Electrostar's)
Windows: toughened glass, 8 main units ~1.6m x ~0.9m ~11-12m^2..
Car body: Desiros are welded aluminium with bolted on steel cabs.

Entered service 2003
Tested at Siemens Northam Depot, Southampton
Owner: Angel Trains
Glazing per side 11-12m^2



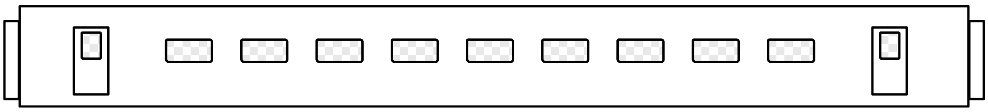
d) **SWR Siemens Class 707 Desiro City**, 100mph 5 x 20m EMU 2+2 seating
1.5m door pairs. Windows: laminated inner glass, 8 main units ~1.6m x ~0.9m ~11-12m^2.
Car body as for Class 450.

Entered service 2017
Tested at SWR Wimbledon Depot.
Owner: Angel Trains
Glazing per side 11-12m^2



e) **C2C\ Great Anglia Bombardier Class 720 Aventra**, 100mph 5 x 24.4m EMU
3+2 seating. 1.7m door pairs. Windows: laminated inner glass,
9 main units: 8 @1.5m x 1m plus 1@1.5m x 0.7m side ~13m^2.
Construction as Electrostar

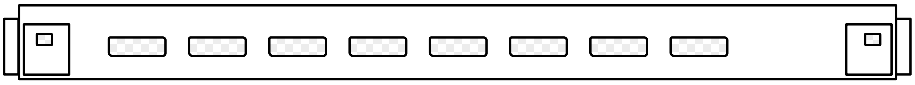
Entered service 2020
Tested with limited access at Bombardier, Litchurch Lane works, Derby
Owner: Porterbrook
Glazing per side ~13m^2



f) **GWR Class 802 Hitachi AT300 125mph Super Express**, 9 or 5 x 26m car bi-mode,
2+2 seating. Windows: laminated inner glass, 9 main units ~1.2m x ~0.6m 6-7 m^2
Car-body: welded aluminium.

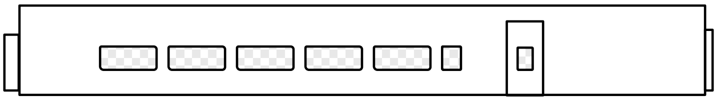
Entered Service 2018
Modelled
Owner: Eversholt UK Rails Group
Glazing per side 6-7m^2

Figure 2 Sketches and details of train carriages tested, modelled and discussed.



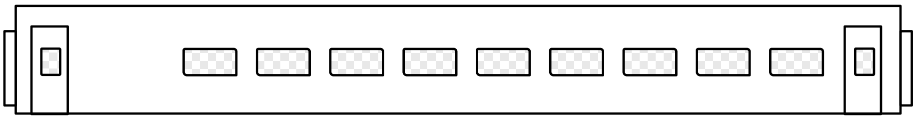
g) **Avanti West Coast Class 390 Alstom Pendolino 140mph tilting express**, up to ~24m x 11 car sets. End doors.
Windows: toughened glass, 8 main units ~1.5m x ~0.6m = 7-8 m^2
Car-body welded aluminium

Entered Service 2002
Discussed
Owner: Angel Trains
Glazing per side 7-8 m^2



h) **Eurostar e300 Alstom Class 373 186mph (300km/h) high speed train**, 387m formation of 20 cars, trailers 18.7m, single side door
Windows: toughened glass, 5 main units plus one small window
5 x 1.5m x 0.6m + 0.5m x 0.6m = ~5m^2
Car-body: welded steel

Entered Service 2003
Discussed
Owner: Eurostar (UK) Ltd
Glazing per side ~5 m^2



i) **Eurostar e320 Siemens Class 374 200mph (320km/h) high speed train**, 390m formation of 16 cars, trailers 24.2m, end doors
Windows: part-laminated glass, 9 main units 9 x 1.4m x 0.7m = ~9m^2
Car-body: welded Aluminium

Entered Service 2015
Discussed
Owner: Eurostar International Ltd.
Glazing per side ~9 m^2

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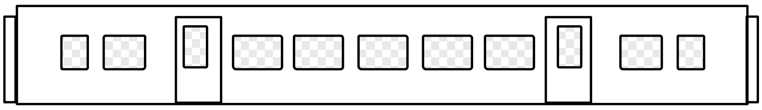


j) **SE Class 395 Hitachi AT300 140mph (250km/h) 6 x 20m EMU**, 2+2 seating, 1.2m side doors. Windows: toughened glass,
5 x 1.3m x 0.9m + 2 x 1.1m x 0.9m + 0.7 x 0.9m = ~ 9m^2
Car-body: welded Aluminium

Entered Service 2011
Discussed
Owner: Eversholt UK Rails Group
Glazing per side ~9 m^2

Figure 2 (continued) Sketches and details of train carriages tested, modelled and discussed.

4 Factors Affecting Radio Frequency Signal Attenuation on Trains

This section explains the prime causes of on-train signal attenuation: User Body Loss (UBL) linked to how the passenger holds and uses their mobile device, Crowding Body Loss (CBL), the signal absorption caused by the bodies and belongings of neighbouring passengers, and Vehicle Penetration Loss (VPL) down to the design and construction of the rail carriage and its internal fittings. This section is based on a literature review [16-20] and the experience of the study team members.

4.1 Body loss

Passengers' bodies absorb mobile signal, and their belongings may absorb, reflect or scatter it too. There are two main causes, User Body Loss relating to handling and use of the mobile device, and Crowding Body Loss linked to the presence of other passengers and their belongings.

All body loss effects vary with:

- Carrier frequency of the mobile signal
- Location of the passenger within the passenger saloon
- The source of the signal, whether a distant land-based transceiver or a ceiling-mounted train-borne gateway access point

For characterization purposes the carrier frequency ranges can be grouped into three spectrum bands:

- Low 700- 900 MHz
- Medium 1,800-2,600 MHz
- High 3,400-5,000 MHz

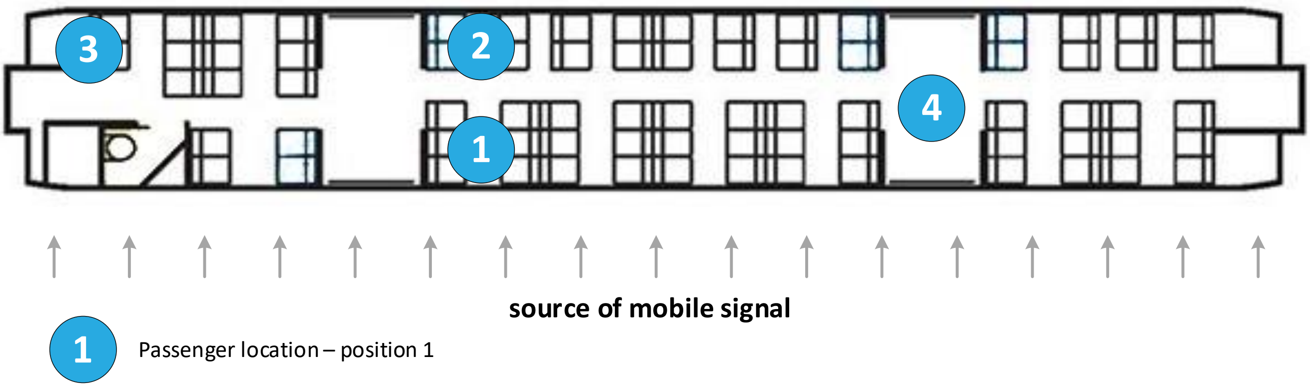


Figure 3 Passenger locations compared by testing.

This study considered four representative passenger locations within the carriage to compare for all direct field connectivity measurements and subsequent modelling (see Figure 3):

- **Position 1** [through window] seated by window closest to the mobile signal source
- **Position 2** [through window] seated across the aisle next to the window opposite **Position 1**
- **Position 3** [through metal] seated deep in the corner of the saloon away from any window or door
- **Position 4** [through door] standing in the middle of the space between doors

Slightly different positions were chosen for modelling of wifi gateways (see Section 6.4 and Figure 13).

4.1.1 User Body Loss from handling and use of mobile devices

The mobile device makes use of the signal power received by its built-in antenna, but this is affected by many factors including the presence of the user's body, especially hand and head, how it is held, and its design.

Mobile devices vary in size and shape and can operate very differently. A smartphone with wired or wireless earbuds or headset is held differently to a mobile phone held directly against the right or left ear. The radio frequency characteristics of devices also vary widely depending on their size and shape and the types, location and configuration of the built-in antennas. The complexity of the receiver's design will also add additional loss and noise.

This study derives a range of 2dB to 20dB for User Body Loss for a passenger using a mobile device operating across any of the available technology and frequency bands. These values are based on studies from the literature.

- 2012 (Aalborg University, Denmark) [16] Functional handset tests comparing the performance of a range of mobile and smartphones available in 2012 operating at 776MHz and 2,300 MHz and fed from two different transmitter locations, tested both as free-standing devices and whilst being carried by users pacing over a short standard 5m walking route. The study found UBL values typically below 6dB but within an overall range between 0dB and 15dB.

- 2015 (UL for Ofcom) [20] Formal industry handset tests in a controlled environment (mobile device configured with simulated head and/ or hand within an anechoic chamber) for 2G, 3G and 4G technologies and frequency spectrum. UBL was found to vary by technology (average 12dB, range 2-20dB (2G), average 10dB range 3-20 dB(3G), and average 6dB, range 3-12dB (4G)) but also varied by up to 10dB across different mobile device designs, with phones held in the left hand up to 10dB worse than in the right hand.

- 2018 (Aalborg University, Denmark)[19] Industry-style handset tests on a range of 16 popular smartphones (including one older mobile phone design) in a controlled environment (mobile device configured with simulated head and/ or hand within an anechoic chamber) at 800-900 MHz and 1,800-2,500MHz for both normal telephony and data (browsing and apps). This study also looked at how sensitive UBL was to handling of the device – the paper reported overall results consistent with 2012 but found the sensitivity to handling was a range of 0-6dB for the best performing devices, but as much as 16dB for the worst (and a range of 10dB between left-handed and right-handed use).

The 2-20 dB range also considers the different passenger locations considered as device usage may be different for seated and standing passengers (see Figure 3).

4.1.2 Crowding Body Loss from the bodies and belongings of other passengers

Crowding Body Loss is caused by the bodies of adjacent passengers and their belongings. Potential crowding scenarios are most likely to affect passenger locations 2 to 4 within Figure 3:

- Position 2 – passenger seated by a window but on the far side of the train with all seats taken, luggage racks full and the aisle blocked by standing passengers – space is available to use the mobile device at ear, lap or table

- Position 3 – passenger seated deep in the corner of the train, away from a window and surrounded by standing passengers with their belongings – space to use mobile device at ear, lap or table

- Position 4 – passenger standing between doors crowded in by standing passengers and their belongings on either side, space to use mobile device is limited so it is more likely to be in a pocket or bag accessed via earbuds or headset

The literature review did not find evidence of direct attempts to measure Crowding Body Loss on a train but did find evidence of work conducted in 1977-79 by Yamaura in Japan [17, 18] to assess signal absorption through the chest and abdomen of the human body. Yamaura's aim was to demonstrate a laboratory concept of a potential 'RF stethoscope' for medical imaging operating at between 1,800MHz and 2,700 MHz. Table 5 shows the through body signal attenuation measured through the human chest and abdomen assuming a torso of constant 180mm thickness from front to back.

Body tissue	Method	Attenuation *	Comment
Solid Muscle	Theoretical	55 - 100 dB	Increasing 1 - 3 GHz (wide range)
Abdomen	Measurement	70 - 90 dB	Increasing 1.8 - 2.4 GHz
Left Thorax (including heart)	Measurement	70 - 85 dB	Increasing 1.8 - 2.4 GHz
Right Thorax (lung)	Measurement	50 - 70 dB	Increasing 1.8 - 2.7 GHz
Solid fat	Theoretical	15 - 20 dB	Increasing 1 - 3 GHz (wide range)

* Converted from original units of Neper/m (1 Neper/m = 8.68 dB/m)

Table 5 RF signal attenuation of the human body
Source: Yamaura 1977 [18]

Yamaura predicted that the signal attenuation through a single 180mm deep body of solid muscle at 2,000 MHz (2 GHz) would be 77dB, a substantial figure. On a train there will be more bodies but also some space for radio frequencies to propagate through the gaps.

This study assumes a wide **Crowding Body Loss range between none (0dB) on empty trains and up to 60dB** for a passenger in Locations 3 or 4 on a crush-laden commuter train (although probably worse for a passenger standing in an inter-carriage gangway).

4.1.3 Body loss assumptions used for modelling

The actual range of combined User and Crowding Body Loss assumed during the modelling presented in Section 6 makes more conservative assumptions of between 2dB and 30dB as shown in Table 6.

Passenger Location	Attenuation Low (700 – 900 MHz)	Attenuation Medium (1,800 – 2,600 MHz)	Attenuation High (3,400 – 5,800 MHz)
Position 1 near window, seated	10 dB (train empty or full)	10 dB (train empty or full)	2 dB (train empty or full)
Position 2 far window, seated	10 dB (empty) 25 dB (full)	10 dB (empty) 30 dB (full)	2 dB (empty) 22 dB (full)
Position 3 through metal, seated	10 dB (empty) 25 dB (full)	10 dB (empty) 30 dB (full)	2 dB (empty) 22 dB (full)
Position 4 through door, standing	10 dB (empty) 15 dB (full)	10 dB (empty) 20 dB (full)	2 dB (empty) 20 dB (full)

Table 6 User and Crowding Body Loss assumptions used for modelling

Note that the attenuation values in Table 6 for empty trains in the higher frequency range are reduced. This might seem counter-intuitive but is based on an assumption that these frequencies are typically used for high-capacity data services (not for voice services) with the device out on a table or located in the passenger’s hand. Attenuation would be higher if the device is out of sight in a pocket or bag.

The modelling discussed later in Section 6.4 also assumes a total range of body loss of just 2 to 10 dB for train-borne wifi modelling equivalent to a window seat (Position 1) in Table 6.

4.2 Vehicle Penetration Loss

4.2.1 Overview

Operational and commercial factors influence much of the design of train carriages in terms of length, internal layout and the size and location of doors and bodyside windows, subject to safety and environmental standards and whole life economics.

VPL is the signal attenuation caused by the design and construction of the rail carriage itself, the focus of this study. For a train traversing a line of route exposed to one or more land - or trackside - based mobile signal sources, the signal must enter the interior of the rail carriage through the external surface of the train and then propagate within the rail carriage where it may be absorbed, reflected, and scattered by fixtures and fittings within the train.

Radio frequency signals are also prone to multi-path fading because the scattered and reflected waves interfere constructively and destructively leading to constantly varying peaks and dips in signal strength, including that received by passengers' mobile devices.

The effect of VPL on the signal reaching a passenger's mobile device also depends on several factors independent of train design including:

- Where the passengers are located within the carriage
- The mobile signal carrier frequency – although the range of RF signals in air tends to decrease with frequency, the strength is limited within a 26m by 3m rail carriage compared to differences in signal absorption, reflection and scattering as it interacts with the fabric of the train
- The Angle of Arrival of the mobile signal (see Figure 4) – this varies constantly according to the location of the train along the line of route and the strongest external source of mobile signal, however, it affects propagation through the exterior of the train into the rail carriage and then propagation within the passenger saloon, it also affects the amount of body loss as the signal takes different paths throughout the rail carriage

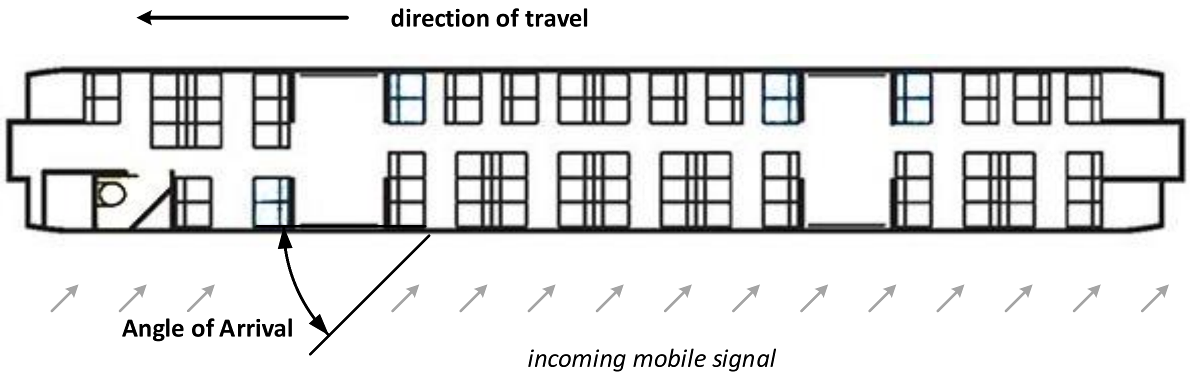


Figure 4 Angle of Arrival of mobile signal

There are four main elements of train design and construction that determine the VPL of the train itself:

- Car body and external doors
- Bodyside Windows and glazing materials
- Other features to improve thermal and acoustic insulation and the efficiency of air conditioning systems
- Interior layout and fixtures and fittings, including seats, tables, luggage racks and other storage areas, toilet cubicles, catering facilities and gangways

The first three relate to signal penetration through the exterior 'skin' of the rail carriage. The last relates to propagation within the rail carriage itself. The sketches and supporting data in Figure 2 (see Section 3.2) compare some of these characteristics for ten different rail carriages. These include the six carriages tested or modelled plus four others for comparative purposes.

4.2.2 Structure of car body and cutouts for doors and windows

All GB passenger trains since the mid-1970s have adopted the ‘monocoque’ design from the car industry to use the bottom, top and side panels as strength members and avoid the need for a separate chassis. This simplifies manufacture and reduces weight whilst strengthening the crashworthiness of the cab and passenger compartments.

The BR Mk III trailer was the first monocoque design of GB mainline rail carriage. The car body and end doors were made from steel. Most suppliers of recent GB fleets including Siemens, Hitachi, CAF and Stadler have all sold rail carriages built from strong, light, welded-aluminium car bodies. Bombardier also uses aluminium, but clamps the longitudinal extrusions to the carriage ends with ‘huck bolts’ (hybrid bolt/rivet) rather than hot welding. Door suppliers have also tended to supply aluminium door panels although new composite material alternatives are becoming available.

Metal car bodies tend to block RF signal, so propagation into the passenger saloon relies on the cutouts for bodyside windows and doors and other ducts/ holes used to route cables and services and sometimes hidden behind Glass-Reinforced Plastic (GRP) panels. The metal skin acts as a ‘Faraday Cage’ reflecting most of the signal through the induction of opposing electric currents within the metal skin. RF screening is greatest for high conductivity metals such as aluminium (seven times more conductive than steel), especially if welded together to maximise electrical continuity. It is not known if the RF electrical continuity of huck bolt fixtures used by Bombardier is any ‘worse’ than welded joints. The window cutouts allow most RF signal to enter directly by transmission through the glazed window itself and is scattered by reflection and diffraction at the edges and corners of the windows. So, a larger area of bodyside glass is more beneficial. However, the quantity of signal entering the train also depends on the type of window glazing used, as discussed in the next section.

Figure 2 in Section 3.2 shows how the car bodies compare for the five different carriage types tested and the RF measurement results discussed in Section 5.2.2.

4.2.3 Window Glazing

Since window cut-outs are the primary point of access for mobile signal, low VPL depends on large areas of bodyside glazing transparent to radio frequencies as well as light.

Bodyside windows fitted with double-glazed plain glass, whether toughened or laminated, lose less than 3dB of signal. This is the glass fitted to GB train bodyside windows (see box below).

Bodyside glazing – GB focus on passenger containment vs European focus on thermal efficiency

GB: GB rolling stock standards have increasingly aligned with European Union practice (for example, the Locomotive and Passenger Technical Specification for Interoperability [21]) but GB industry bodies and safety authorities have obtained some derogations, including for bodyside windows (National Notified Technical Rule GM/RT2100 [22] and Rail Industry Standard RIS-2780-RST [23]).

These new standards were implemented in 2012 in response to research following the Ufton Nervet train derailment on 6th November 2004 [24]. GB standards require the fitment of double-glazed glass bodyside window units comprising a plain laminated glass inner with a conventional toughened glass outer pane. The single laminated pane is intended to reduce the severity of injuries during a violent collision or derailment by containing passengers within the passenger saloon. Only one pane is laminated to aid emergency evacuation or access by emergency services. There is also a desire to reduce the time taken to replace damaged windows, which means window units are also typically specified to be quick and convenient to replace.

European: European railways have focused on improved solar and thermal efficiency by applying low emissivity metallic coatings to reduce the burden of solar gain on air conditioning during the summer and reduce the loss of heat from carriages in winter. Unfortunately, such coatings also reflect radio frequencies, representing an additional Vehicle Penetration Loss of 20-30 dB.

New technical workarounds have been developed, which involves the removal of ~2.5% of the metallic coating in a specific pattern. This retains most of the solar and thermal performance while letting most of the mobile signal back through [25, 26].

Polymer films are also available, subject to rail crashworthiness standards, for external and internal application. Anti-solar film on the outer pane reflects infrared and blocks ultra-violet radiation. Anti-graffiti films on the inner pane resist gouging and scratching of the glass. Any such products that included metal content would reduce RF propagation (see box). However, non-metallic alternatives are available that are claimed to be transparent to radio frequencies [27, 28].

4.2.4 Other external factors

Train designers are under pressure to improve thermal efficiency and reductions in acoustic noise and vibration within the rail carriage to improve the ambience for passengers and the effectiveness of air conditioning systems. This has involved tighter tolerances and sealing of windows and of external doors that also may reduce opportunities for RF signal to leak into and out of the rail carriage.

4.2.5 Interior layout of rail carriage

VPL will also vary with where passengers choose to sit, stand or perch. The choice of interior layout and fixtures and fittings is usually driven by market segment and operational requirements. Rail carriages need to accommodate as many passengers as possible whether seated or standing, with doors spaced and sized to expedite boarding and alighting at stations. Other fixtures provide essential amenities such as luggage and other storage racks, toilet cubicles, catering facilities, waste bins, staff accommodation, and gangways between adjacent carriages. Fixtures and fittings must also meet applicable safety standards to reduce the risk of death or injury under normal and emergency conditions.

The main differences between the interiors of the trains are:

- Length of carriage
- Number, width and location of external doorways and associated lobby or standing areas
- Seat design and layout (seating density and direction: pitch lengthways, seating pattern width ways 2+3, 2+2, 2+1, 1+1, the presence of tables, the width of the aisles, the height of seat backs)
- Location of luggage racks and other storage areas, catering facilities and toilet cubicles

5 Radio Frequency Vehicle Penetration Loss Measurements

This section presents the results of radio frequency measurements of VPL caused by the design and construction of the rail carriage.

5.1 Test Scenarios

All testing was undertaken at a depot road or within maintenance or manufacturing sheds (see Figure 2 in Section 3.2 for details). This provided safe access, mains power and other facilities but was not ideal for RF testing as:

- The transmitting test antenna could only be positioned up to 3m away from the car body, not far enough away to separate 'far field' performance of a land-based transceiver from 'near field' effects

- The proximity to so many other external metal objects and surfaces able to reflect and scatter RF signals, in particular when measured inside a depot shed, will have affected multi-path interactions and hence the results

However, the results measured could be obtained repeatably and the overall range of VPL results recorded provides a useful indication of the effect of train design on the mobile connectivity experience for rail passengers.

Radio frequency measurements were made with calibrated transmit and receive antennas using a 'portable laboratory style' test kit to generate and measure a continuous wave (CW) signal. This set up (Figure 5) was able to measure the variation of VPL under the different identified scenarios already introduced in Sections 2.3 and 4 using low, medium and high spot frequencies between 700 and 5,500 MHz to address the 2G (GSM), 3G (UMTS), 4G (LTE) and 5G (NR) generations of mobile and wifi technology:

- Four representative passenger locations (see Figure 3 in Section 4.1) to investigate the effect of glazing 'through window' (Positions 1 and 2), the car body 'through metal' (Position 3) and standing in doorway 'through door' (Position 4)

- A range of different Angles of Arrival (see Figure 4 in Section 4.2.1), mainly 90°, 45° or 30° although one set of measurements was made at 5°

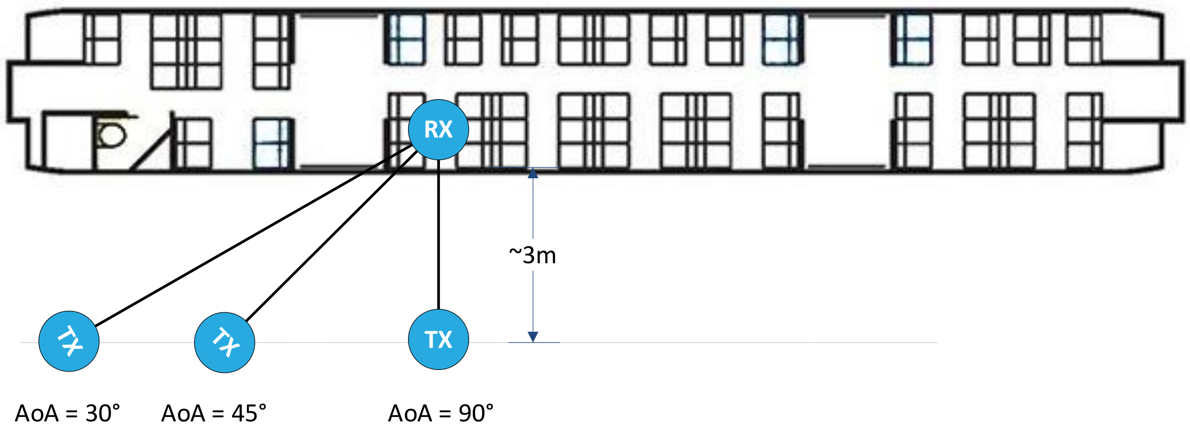


Figure 5 Position 1 test setup showing transmitter and receiver antenna locations

No measurements of in-carriage wifi propagation were completed during the scaled-back test sessions to work around Covid-19 restrictions. However, some theoretical modelling is reported in Section 6.4.

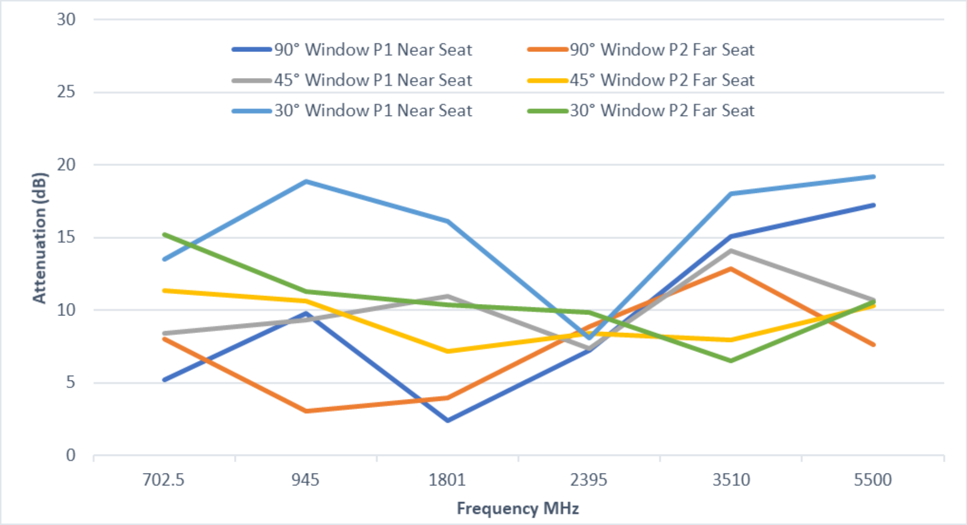
5.1.1 Direct connectivity to remote mast

The results are presented as a series of charts:

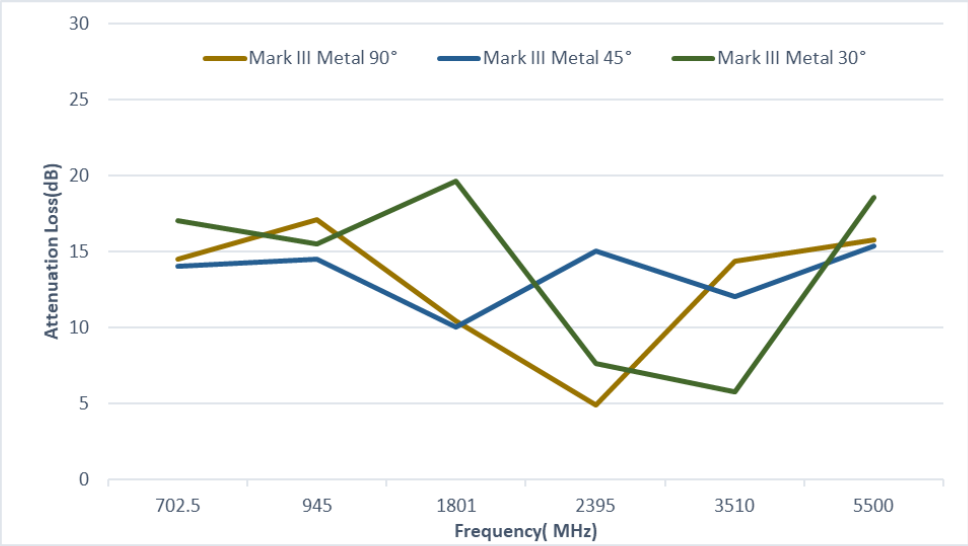
- Figure 6 1975+ British Rail Mark III trailer carriage
- Figure 7 2000 Bombardier Class 357 Electrostar 100 mph 4 x 20m Electric Multiple Unit EMU
- Figure 8 2003 Siemens Class 450 Desiro 100 mph 4 x 20m EMU
- Figure 9 2017 Siemens Class 707 Desiro City 100 mph 5 x 20m EMU

There are twelve charts in total (three per Figure). Each represents a specific train and target passenger location with the charts showing different arrival angles.

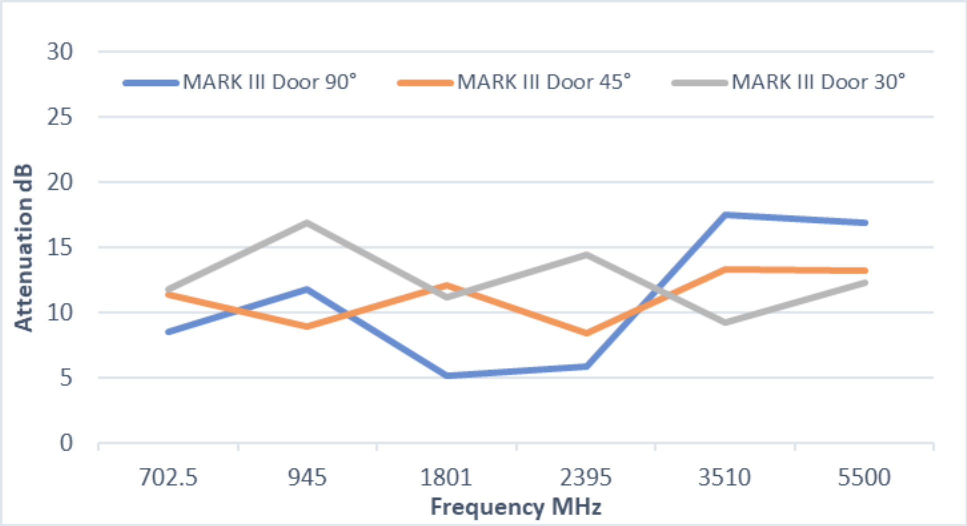
To note, the lines drawn connecting each measured attenuation by spot frequency are an artefact of the chart and should not be used to interpolate the likely attenuation at intermediate frequencies. The VPL attenuation axis is set to show the range of values between 0dB and 30dB.



a) BR Mark III Trailer 'Through Window' Positions 1 and 2

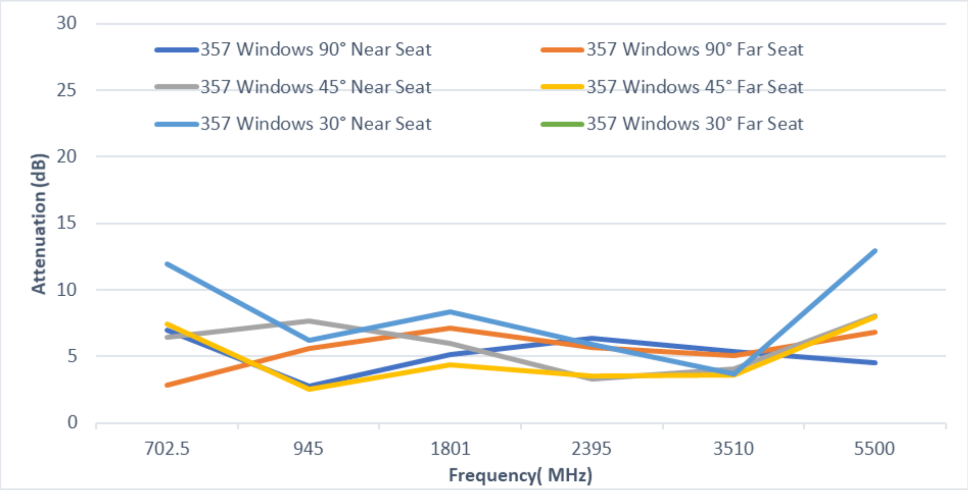


b) BR Mark III Trailer 'Through Metal' Position 3

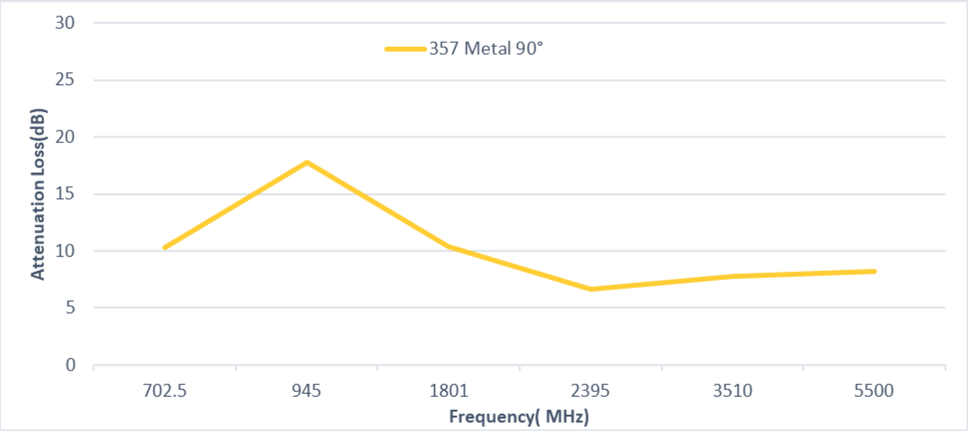


c) BR Mark III Trailer 'Through Door' Position 4

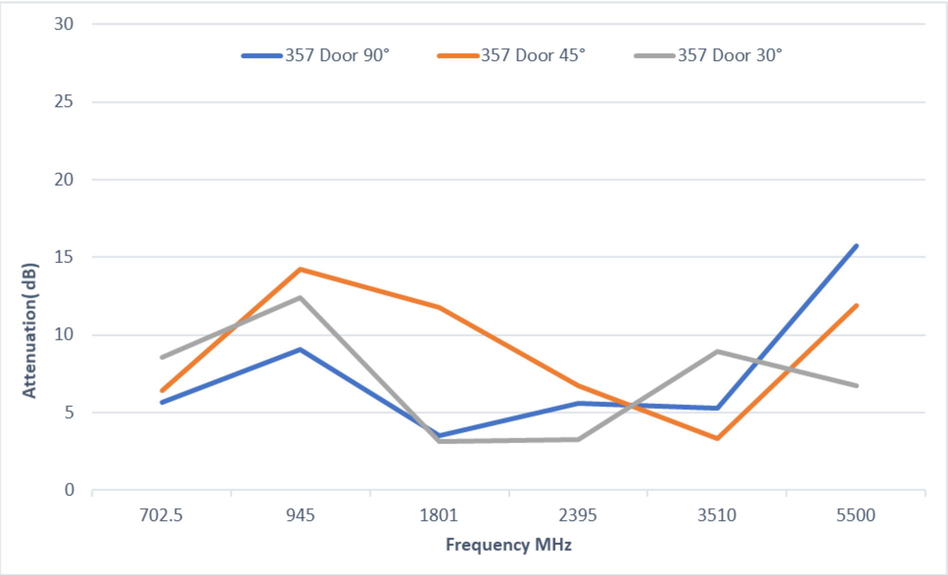
Figure 6 Vehicle Penetration Loss Measurements – BR Mark III Trailer



a) Bombardier Class 357 Electrostar 'Through Window' Positions 1 and 2

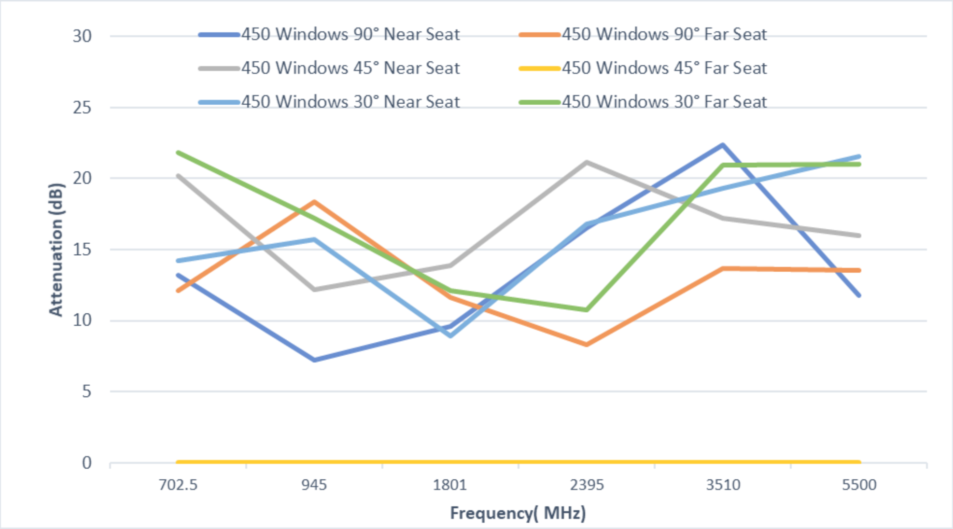


b) Bombardier Class 357 Electrostar 'Through Metal' Position 3

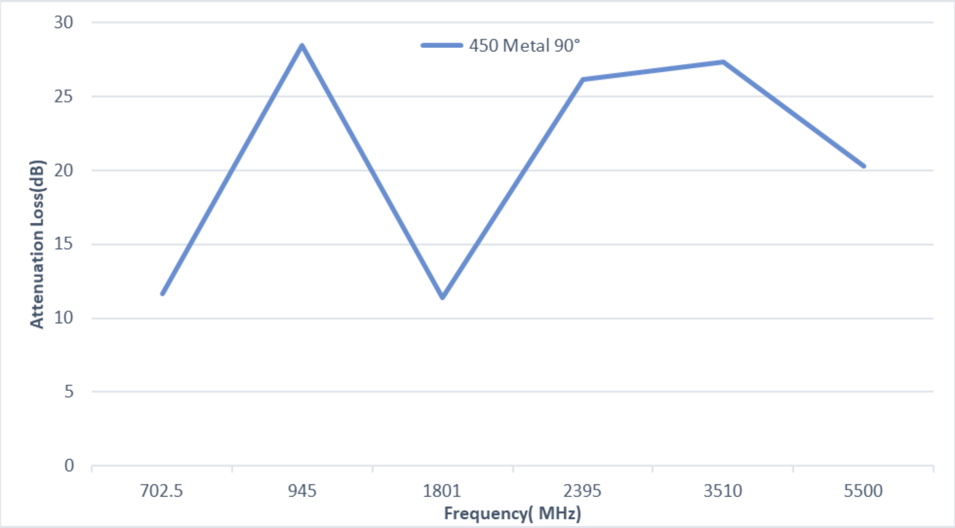


c) Bombardier Class 357 Electrostar 'Through Door' Position 4

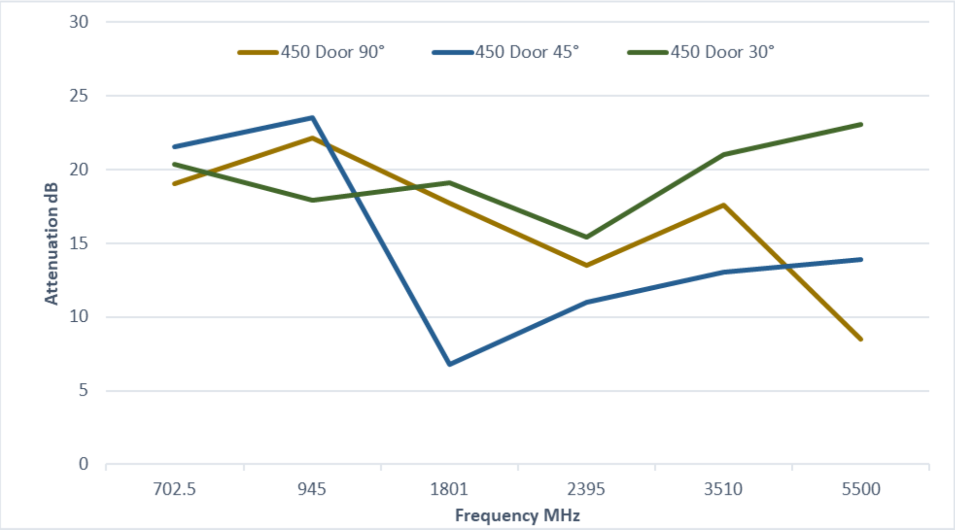
Figure 7 Vehicle Penetration Loss Measurements – Bombardier Class 357 Electrostar



a) Siemens Class 450 Desiro 'Through Window' Positions 1 and 2

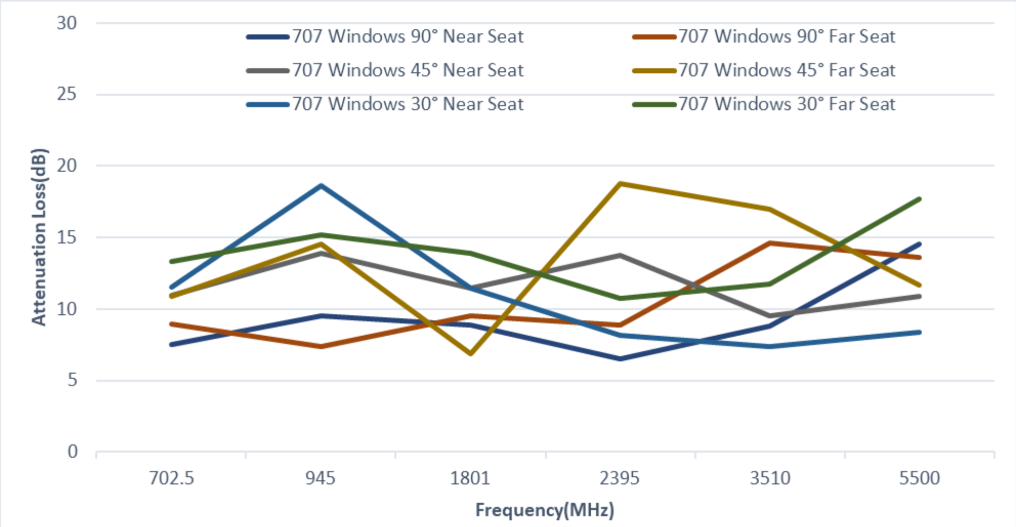


b) Siemens Class 450 Desiro 'Through Metal'Position 3

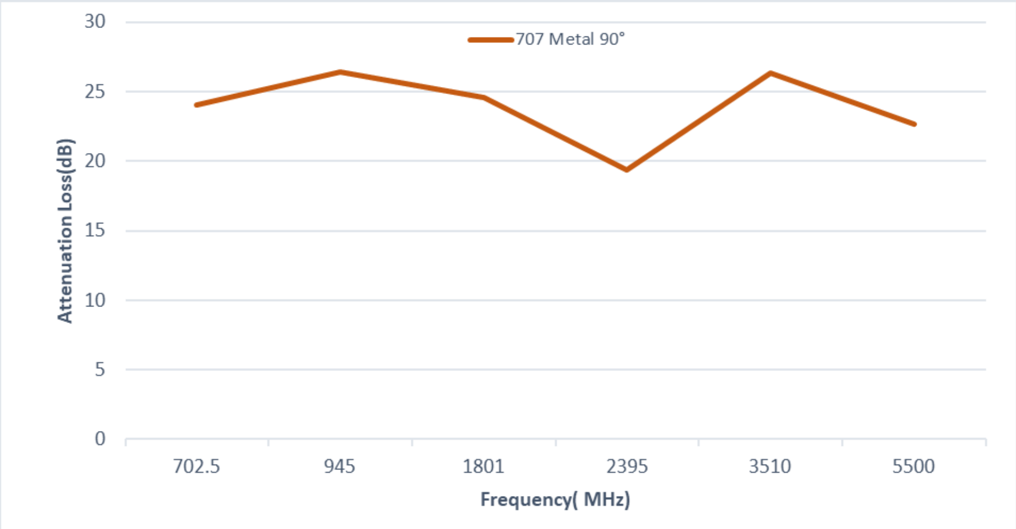


c) Siemens Class 450 Desiro 'Through Door' Position 4

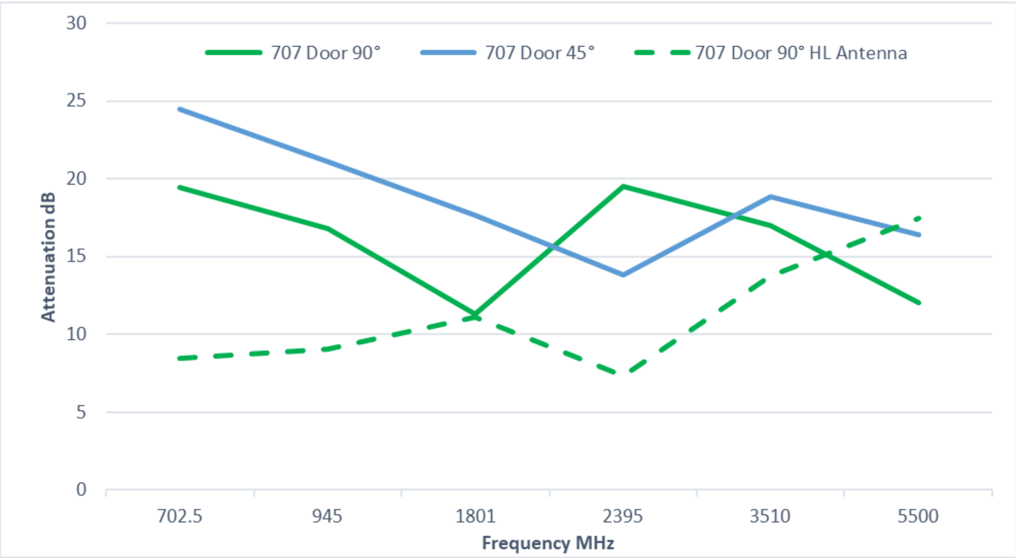
Figure 8 Vehicle Penetration Loss Measurements – Siemens Class 450 Desiro



a) Siemens Class 707 Desiro City 'Through Window' Positions 1 and 2



b) Siemens Class 707 Desiro City 'Through Metal' Position 3



c) Siemens Class 707 Desiro City 'Through Door' Position 4

Figure 9 Vehicle Penetration Loss Measurements – Siemens Class 707 Desiro City

5.1.2 Direct Connectivity to a trackside mast

One additional set of measurements was made for the Siemens Class 707 at SWR Wimbledon depot to simulate VPL at 5° from a mast-mounted trackside transceiver propagating along the line of route.

The transmitting antenna was mounted on a depot bridge at a height of 7.4m and vertical elevation angle of 68° with respect to the vertical. The receiver was placed in the second carriage, at a height of 1.3m and distance of 30m. The range of VPL losses were between 10.8 dB and 13.8 dB at frequencies less than 2,000 MHz, and between 4.4dB and 6.4dB at higher frequencies, an overall range of 4 to 14 dB.

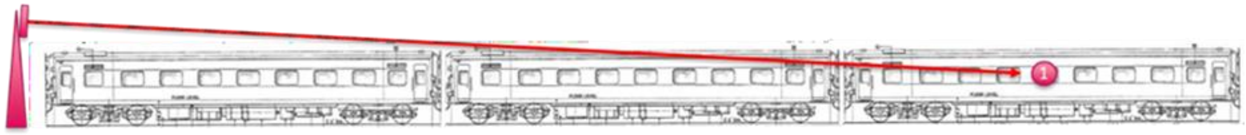


Figure 10 5° measurement to simulate a trackside mast propagating along the line of route

5.2 Discussion of Vehicle Penetration Loss Results

5.2.1 Range of VPL measurements

It is not surprising, given the range of factors discussed in Section 4.2, that VPL measurements vary widely. Each data point reflects a credible instance of a scenario faced by a passenger while travelling on a GB passenger train. However, it is possible to draw practical insights simply by considering the range of VPL values, at each passenger location, for each train, across all Angles of Arrival and signal frequency (Table 7).

Train Carriage	Position 1 and 2 'through window' (dB)	Position 3 'through metal' (dB)	Position 4 'through door' (dB)	Overall (dB)
British Rail HST Mk III Trailer, 1975	3 to 19	5 to 19	5 to 18	3 to 19
Bombardier Cl 357 Electrostar, 2000	3 to 16	7 to 18	3 to 16	3 to 18
Siemens Cl 450 Blue Desiro, 2003	7 to 22	12 to 28	7 to 23	7 to 28
Siemens Cl 707 Desiro City, 2017	7 to 19	19 to 22	7 to 25	7 to 25
Bombardier Cl 720 Aventra, 2020	-	-	-	6 to 14 (limited)
Overall				**3 to 28**

Table 7 Range of Vehicle Penetration Loss measurements

The overall range of VPL measurements is between 3 dB and 28 dB.

The BR Mk III trailer and Bombardier Electrostar have the lowest Vehicle Penetration Loss of 3 dB for a passenger sitting at a window. Both Desiros are slightly worse at 7dB.

The worst results were measured at either Position 3 ('through metal') or 4 ('through door'), with the VPL for the BR Mk III trailer 'rising' to 19 dB and that for the Bombardier Electrostar at 18dB. However, this is still some 6-10dB better (lower) than the Class 450 (28 dB) and Class 707 (25dB) Siemens Desiros at the equivalent positions.

5.2.2 Interpretation of results

It should be noted that each train was tested at a different location so some of the variation may be down to the test conditions. However, if the results are taken at face value, there are potential explanations for the results that relate to train design.

Reasons for differences in minimum VPL results might include:

- All the trains tested appear to be fitted with plain (toughened or laminated) glass to achieve the very low VPL observed at Position 1 ‘through window’ (see also Section 4.2.3)

- It is not known if the Siemens Desiro windows included any plastic coating with any trace of metallic or electrically conducting content that explains the slightly higher 7dB VPL observed (Section 4.2.3), or whether it is due to tighter tolerances and sealing around the window frames or other parts of the carriage that increases the Vehicle Penetration Loss (Section 4.2.4)

Reasons for differences between the maximum VPL values might include:

- The Desiros are welded aluminum frames, which have the highest ‘Faraday Cage’ RF screening effects (ignoring window cutouts) compared to the steel BR Mk III trailer and the huck-bolted aluminum Electrostar

- Improvements in general construction tolerances, acoustic and thermal insulation and sealing compared with the BR MkIII trailer and Bombardier Electrostar

- The amount of bodyside glazing or door layouts – the Siemens Desiros perform worse than the Bombardier Electrostar despite having very similar areas of glazing (11-12m^2) and even the BR Mk III trailer that has a smaller glazing area (9-10m^2) (Figure 2 in Section 3.2).

This suggests that any welded aluminum train, especially those supplied since 2015, with less glazing than the Siemens Desiros (see Table 7) might be anticipated to have a VPL for some passengers higher than 28dB.

By way of comparison the Alstom Class 390 Pendolino, a train with known mobile connectivity issues, has a low glazed window area of 7-8m^2 per carriage side and hence high VPL, as too the High Speed 1 fleets (14-54dB) [14,15]. See also Table 16 in Appendix 3.

The comparison of glazing areas in Table 8 would also suggest the Hitachi Class 801/ Class 802 Super Express bi-modes should also have even worse VPL than the Pendolino, as would the original Eurostar e300 Alstom Class 373.

Train Carriage	Year Introduced	Bodyside Window Glazing (m^2)	Carriage length (m)	Relevance to study
Bombardier Cl 720 Aventra	2020	~13	24.4	Tested (part)
Bombardier Cl 357 Electrostar	2000	11-12	20	Tested
Siemens Cl 450 Blue Desiro	2003	11-12	20	Tested
Siemens Cl 707 Desiro City	2017	11-12	20	Tested
British Rail HST Mk III Trailer	1975	9-10	23	Tested
HS1 Hitachi AT300 Class 395	2011	~ 9	20	Comparator [14, 15]
HS1 Eurostar e320, Siemens Class 374	2015	~ 9	24.2	Comparator [14, 15]
Alstom Class 390 Pendolino	2002	7 – 8	24	Comparator
Hitachi AT300 Class 802 Super Express bi-mode	2018	6 – 7	26	Modelled
HS1 Eurostar e300 Alstom Class 373	2003	~ 5	18.7	Comparator

Table 8 Comparison of bodyside glazing by carriage type, age and length

5.3 Implications for train design

As already discussed in Section 4.2, there are many constraints to reducing the VPL within the GB fleet and, if anything, they are increasing with stricter environmental standards.

5.3.1 The importance of glazing

Whilst GB fleets currently generally benefit from the fitment of plain glass with its excellent RF propagation characteristics (Section 4.2.3), a future priority is to ensure specifications for rail carriage bodyside glazing not only consider the environmental aspects but the VPL implications too - ensuring very low values of VPL are specified. Ideally it needs to remain as good as today's plain glass.

Likewise, specifying a surface area of bodyside window glazing of at least 10m^2 per carriage side is desirable (though noting even this is already less than the 11-12m^2 on today's Desiros).

5.3.2 New construction materials

Suppliers are continuing to investigate the use of composite materials, for example, as an alternative to aluminium for door panel leaves. Such materials may reduce VPL but not if they include a layer of aluminium foil in the composite to reduce heat radiation or act as a water barrier.

Some candidate materials, such as carbon fibre, may be electrically conducting and have their own unique RF blocking characteristics.

6 Train Signal Attenuation Modelling

This section presents the results of the modelling activities to show the overall effect of train signal attenuation on voice and data capacity for a number of scenarios with pre-defined Body Loss and Vehicle Penetration Loss assumptions.

Prediction tool-based modelling was conducted, based on simplified carriage layout assumptions to construct a basic 3D-model of the carriage interior, as well as link budget-based propagation and performance modelling. Projections are also shown for a train-borne wifi gateway. Such RF tool-based models are used to visualise the expected distributions of mobile signal around the rail carriage as 'heat maps'.

6.1 Main Assumptions

The modelling results in this section are based on both link budget calculations and a special network design and modelling software adapted by the study team for railway applications. The tool allows 3D propagation simulations but relies on accurate detailed models of the exterior and interior of rail carriages and the presence of passengers. In the absence of detailed Computer-Aided Design (CAD) information for the trains, the scenarios modelled by this study were based on simplified assumptions about rail carriage design, so are illustrative rather than definitive.

The predictions are based on assumptions recorded in Appendix 2, including the signal levels required to achieve various qualities of voice telephony and data capacity. The prediction results (heatmaps, see Figure 15 in Section 6.5) were compared with the RF link budget-based calculations (see Figure 11) to ensure consistency. Although the prediction tool simulated results that are in the right range, in absence of exact carriage design and window losses, there is some variance.

The link between technology generation, available signal bandwidth, and the relationship between signal power and 4G/ 5G data throughput is already shown in Figure 1, Section 2.2.

The model was able to model 'far field' propagation by setting the signal source at a distance of 250m from the middle of the train at a height of 10m and irradiating the exterior of the train with -90dBm of signal power using metrics appropriate to the mobile technology (as explained in Section 2.2 and Table 2).

The BL assumptions (Table 6 in Section 4.1.3) assume a crowding loss no greater than 20dB (on top of UBL) although some passengers on heavily-laden trains may experience far worse (the assumption of up to 60dB proposed in Section 4.1.2).

The VPL modelled appears to be confined to a range of 15 to 25dB. These seem consistent with the test results reported in Section 5 but may be optimistic for the modelled Hitachi Class 802 with its greatly reduced glazing (Figure 2).

6.2 Direct Connectivity – Voice Quality

These modelled scenarios, based on link budgets and real measurement, are presented in Figure 11 as a series of bar charts projecting voice quality of service levels (see Appendix 2.1 Table 14) for each frequency band [900MHz (2G), 1,800MHz (3G and 4G), 2,600 MHz (4G), 700MHz (5G) and 3,500 MHz (5G)] for the six rail carriages modelled (including the Class 802 that was modelled but not tested):

a) Position 1 window location, 90° Angle of arrival (assumed to behave the same for empty or loaded train)

b) Position 1 window location, 30° Angle of arrival (assumed to behave the same for empty or loaded train)

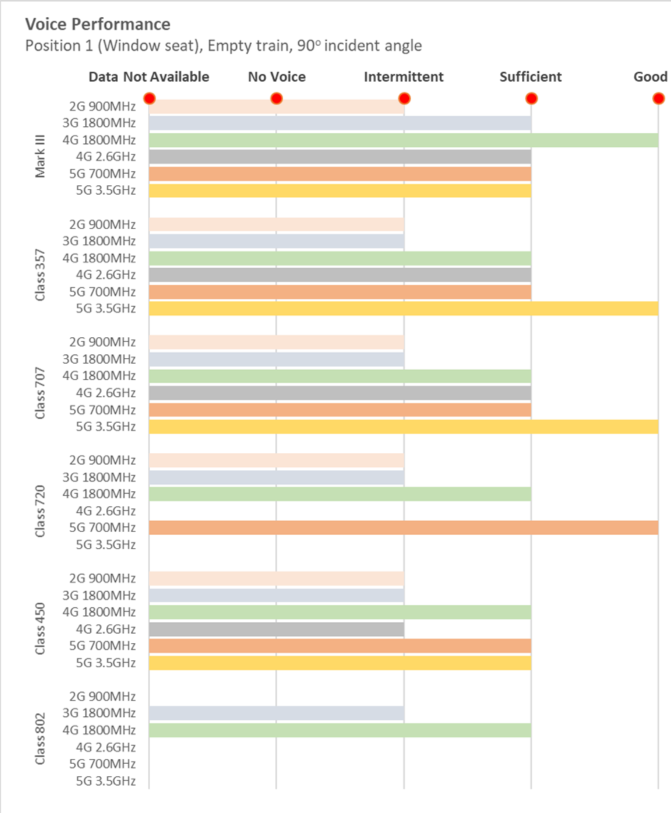
c) Position 3 corner location, 90° Angle of arrival (empty train)

d) Position 3 corner location, 90° Angle of arrival (loaded train)

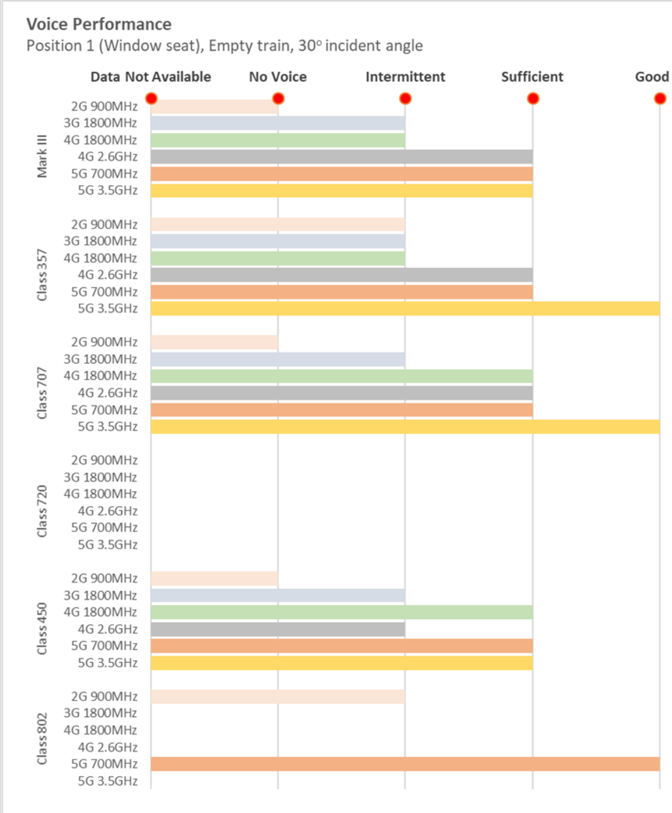
e) Position 4 doorway standing location, 90° Angle of arrival (empty train)

f) Position 4 doorway standing location, 90° Angle of arrival (loaded train)

These projections suggest reasonable connectivity on lightly loaded trains but poor mobile connectivity for any passengers sitting in corner seats or standing in the doorways of loaded trains. The BR MkIII and Bombardier Electrostar may just about allow a connection.

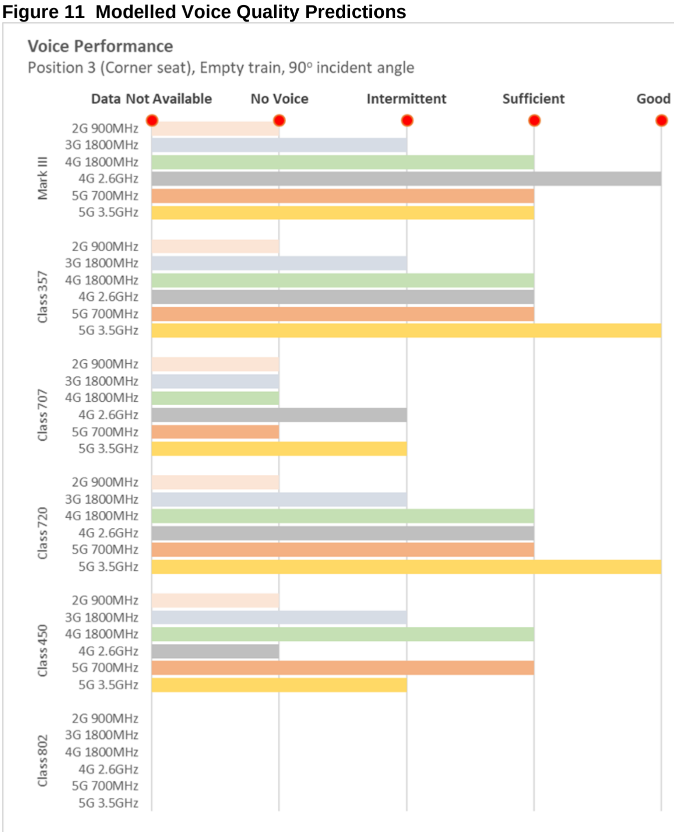


a) Voice calls Position 1 window 90° empty or loaded

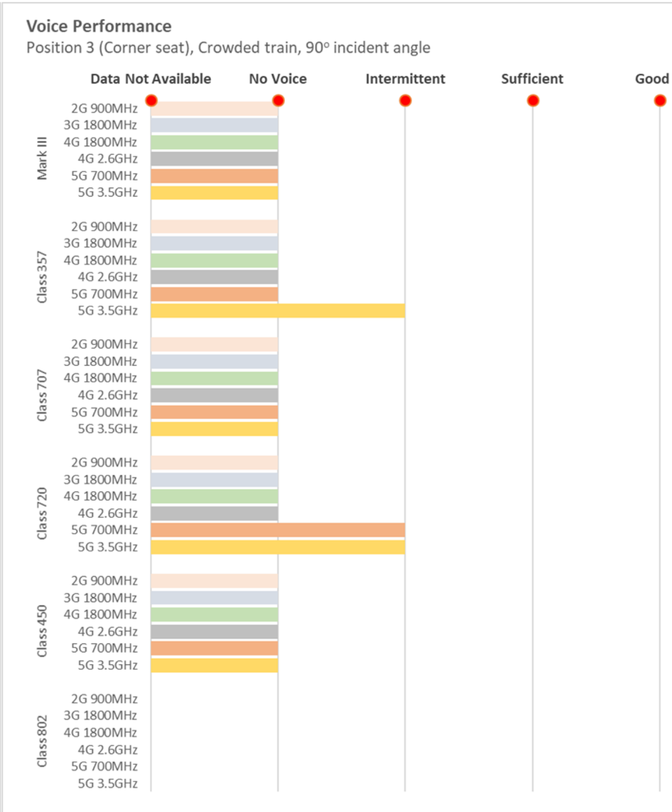


b) Voice calls Position 1 window 30° empty or loaded

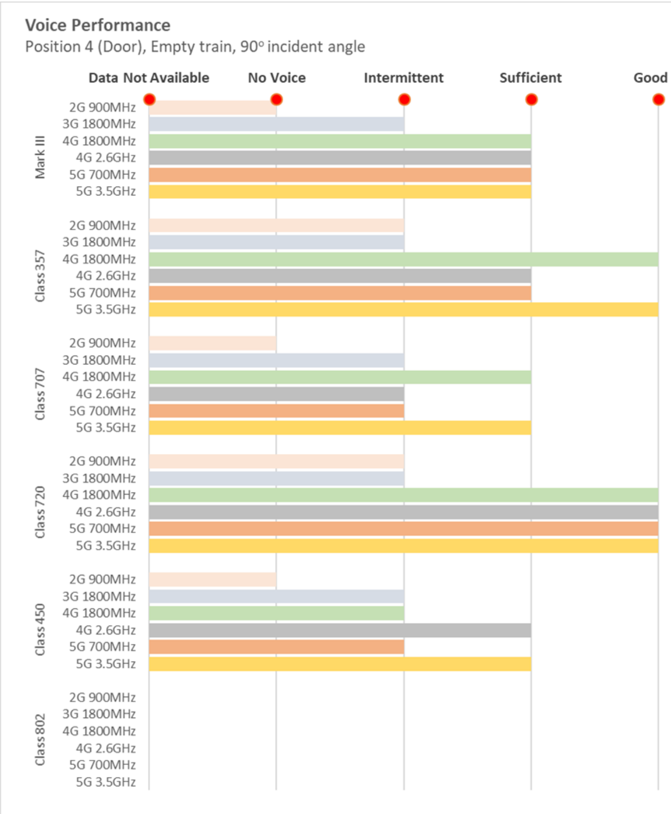
Figure 11 Modelled Voice Quality Predictions



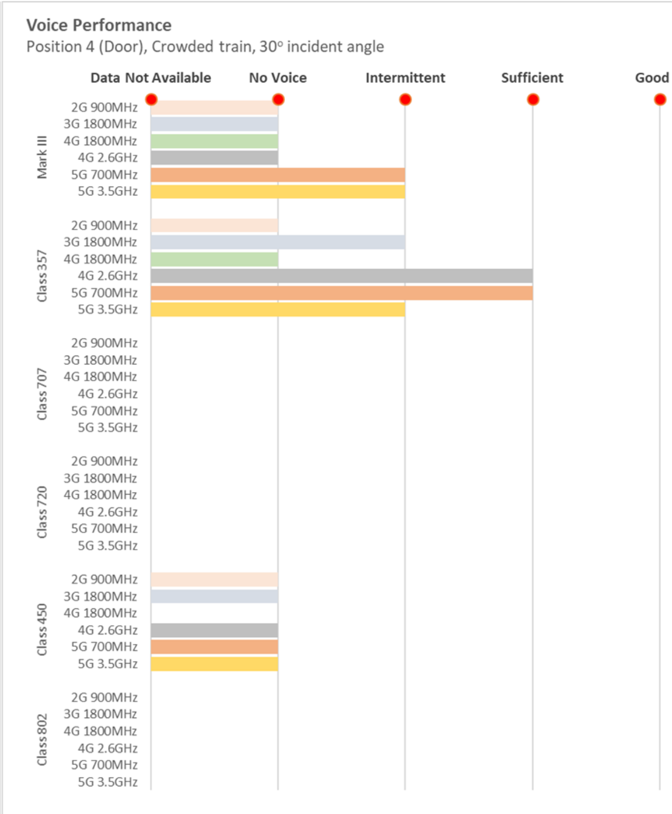
c) Voice callsPosition 3 corner 90° empty



d) Voice calls Position 3 corner 90° loaded



e) Voice, Position 4 doorway 90° empty



f) Voice, Position 4 doorway 30° loaded

Figure 12 Modelled Voice Quality Predictions

6.3 Direct Connectivity – 4G/ 5G Data Capacity

These modelled scenarios, based on link budgets and real measurement, are presented in Figure 12 as a series of bar charts projecting achievable data capacity (based on Figure 1 in Section 2.2) for each 4G or 5G frequency band for the six rail carriages tested (and including the Class 802 that was only modelled).

The solid bar shows the typical data capacity achieved by a passenger's mobile device on the train while the unfilled bar shows the data capacity expected to be available trackside outside the train (>100Mbps). However, this contrasts with Figure 1 (Section 2.2) that suggests a wider range of data capacity between 25 Mbps and 250 Mbps for a signal level of -90dBm.

Figure 12 shows six scenarios:

a) Position 1 window location, 90° Angle of arrival (assumed the same for empty or loaded train)

b) Position 1 window location, 30° Angle of arrival (assumed the same for empty or loaded train)

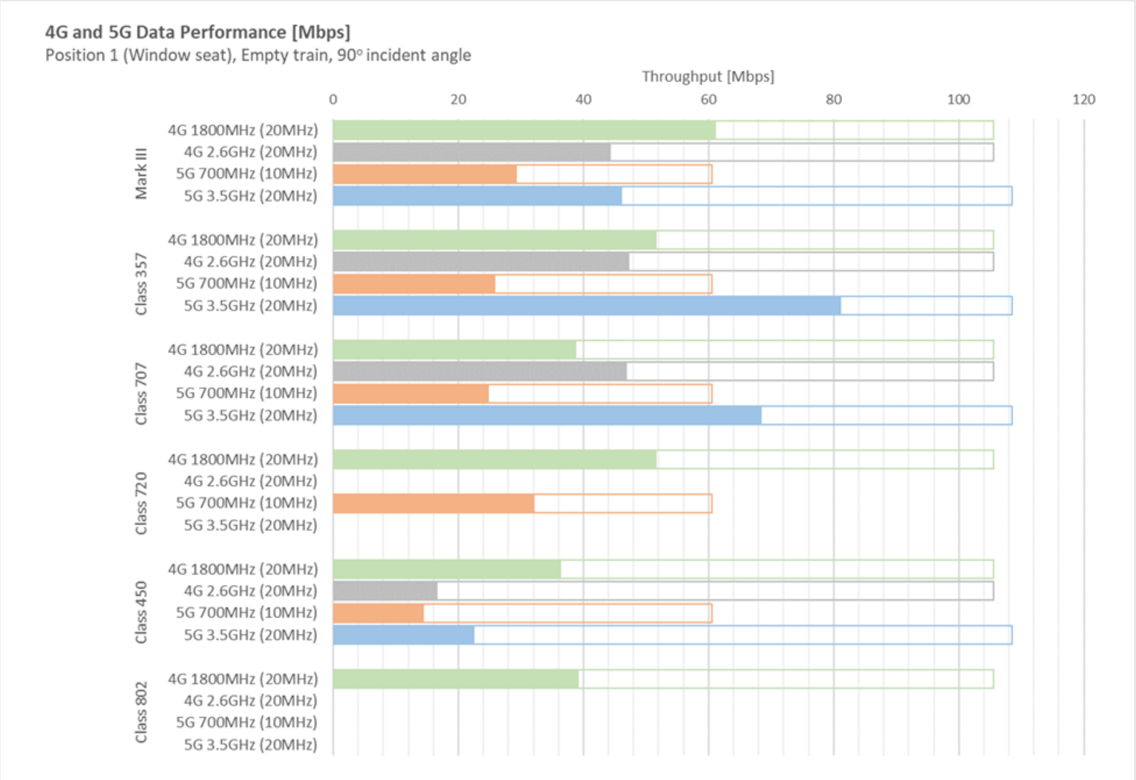
c) Position 3 corner location, 90° Angle of arrival (empty train)

d) Position 3 corner location, 90° Angle of arrival (loaded train)

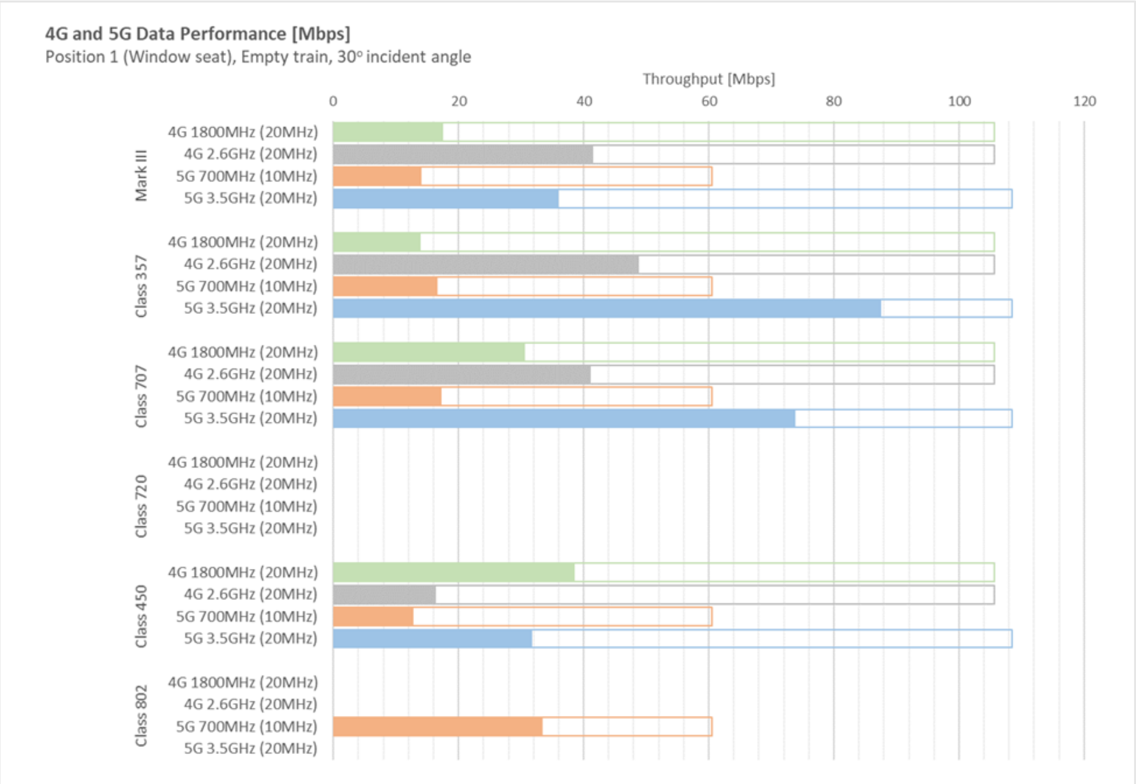
e) Position 4 doorway standing location, 90° Angle of arrival (empty train)

f) Position 4 doorway standing location, 90° Angle of arrival (loaded train)

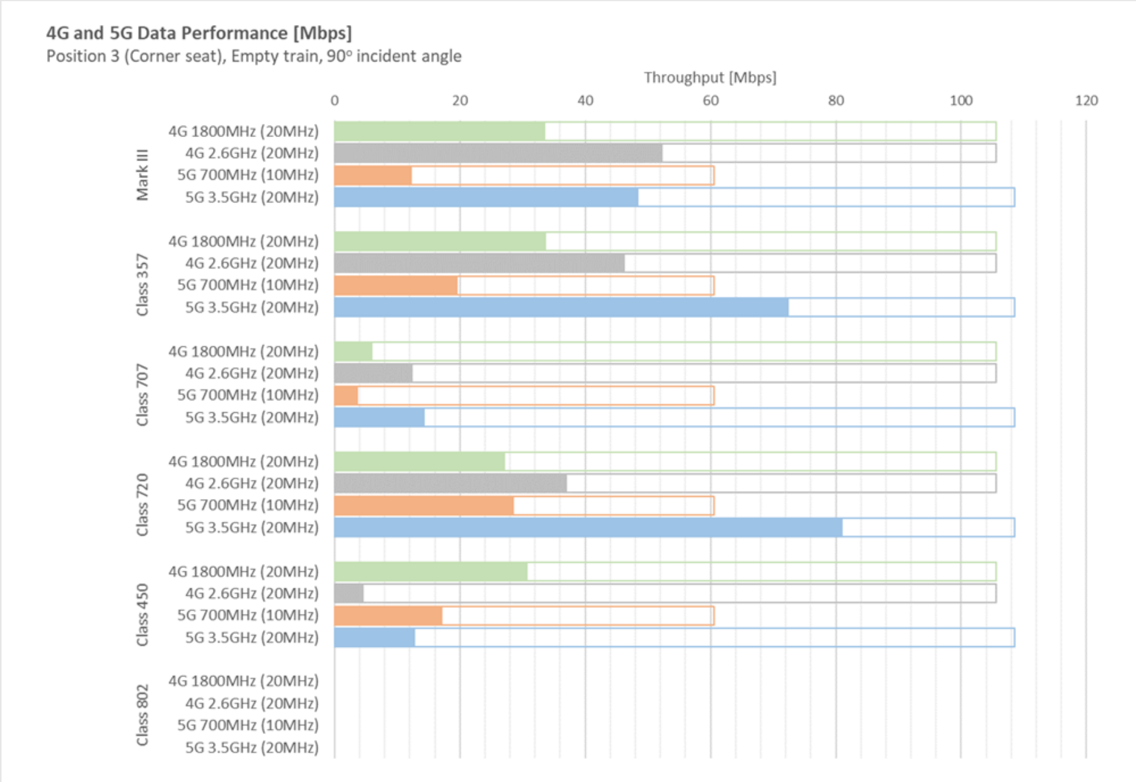
These projections predict no data capacity on the Hitachi Class 802 except for a 700MHz 5G signal to a window seat when the train is pointing in a favourable direction. Otherwise lightly laden trains should allow passengers data rates of between 10-80 Mbps. Loaded Siemens Desiros offer no data capacity in corner seats or in doorways.



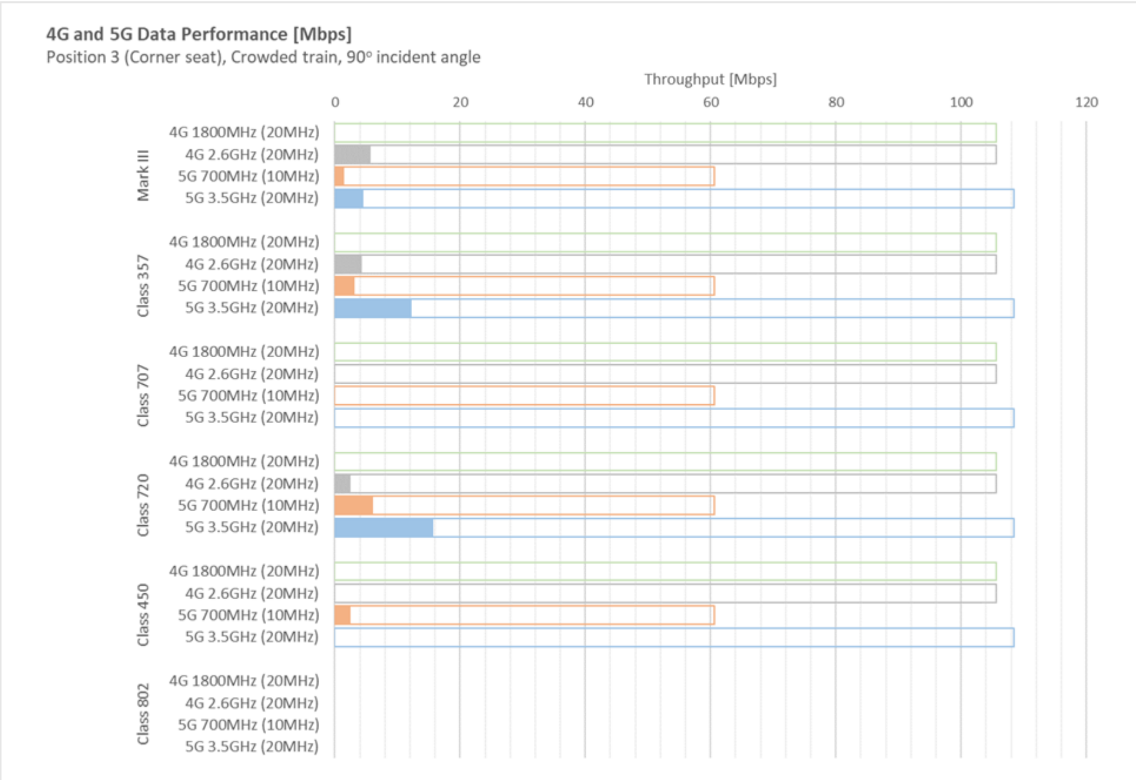
a) Data capacity, Position 1 window 90° empty v open trackside



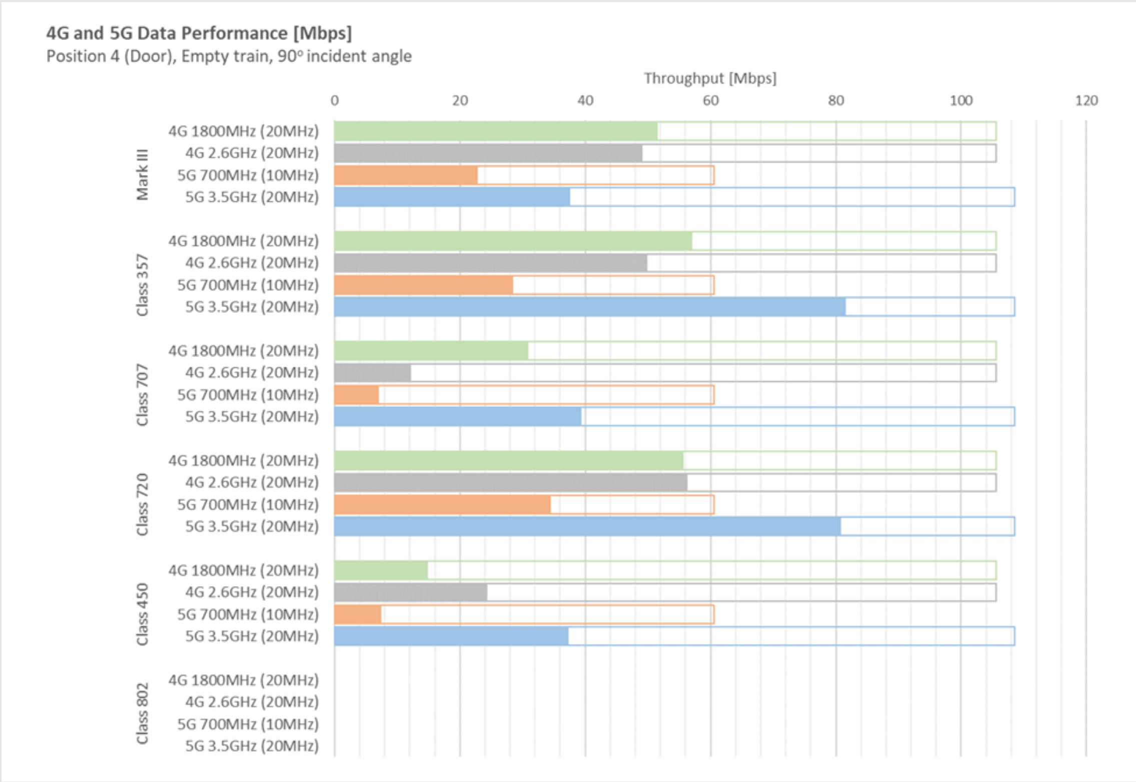
b) Data capacity, Position 1 window 30° empty v open trackside



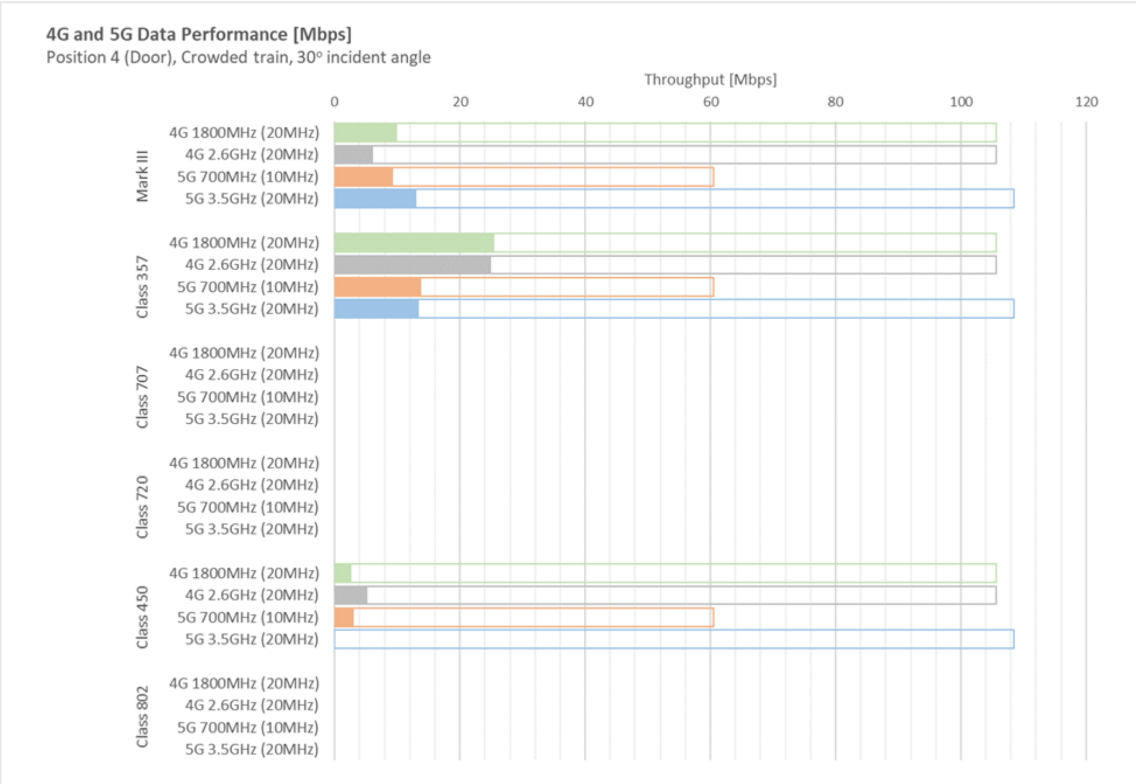
c) Data capacity, Position 3 corner 90° empty v open trackside



d) Data capacity, Position 3 corner 90° loaded v open trackside



e) Data capacity, Position 4 door 90° empty v open trackside



f) Data capacity, Position 4 door 90° loaded v open trackside

Figure 13 Modelled Data Capacity Quality Predictions for 4G/ 5G Services

6.4 Train-borne Gateway – Single User Wifi Access Point Data Capacity

A worst-case scenario with a wifi access point located at one end of the carriage was modelled for data capacity direct to six passenger locations labelled 21-26 (see Figure 13). The VPL was considered equivalent to direct connectivity to a window seat (Table 6 in Section 4.1.3) with no CBL element. Modelling did predict that higher frequencies would experience higher propagation loss along the length of the carriage, including the effect of reflections and scatter from fixtures and fittings and passengers.

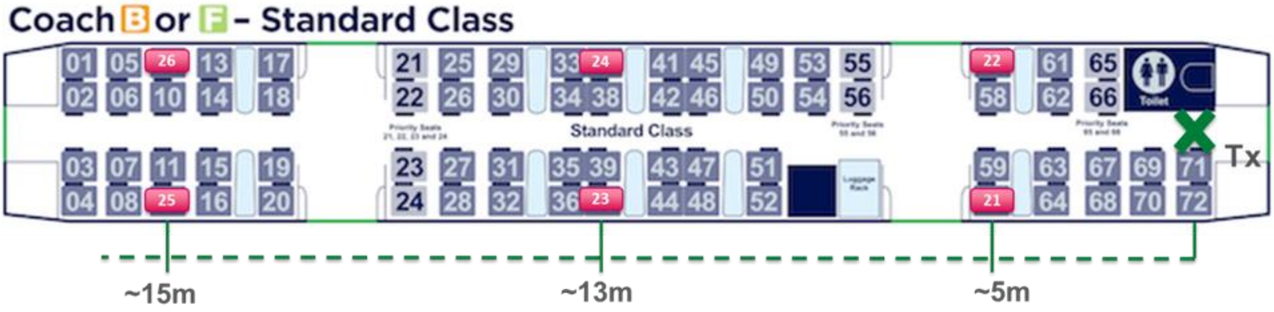


Figure 14 Passenger locations assumed for wifi modelling

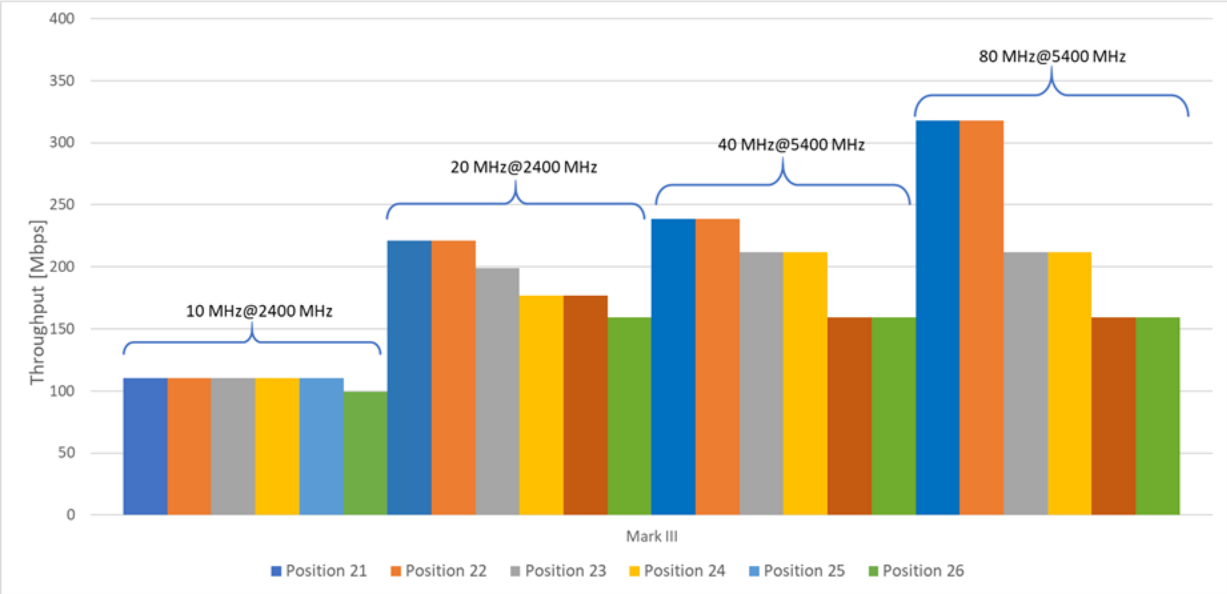
The model assumed a wifi 6 access point (IEEE 802.11ax) and a transmit power (EIRP) of 23 dBm.

The modelled wifi scenarios are presented in Figure 14 as a series of bar charts projecting achievable data capacity (based on Figure 1 in Section 2.2) at 2.4 GHz or 5.4 GHz at the six monitoring locations for a range of available frequencies and bandwidths:

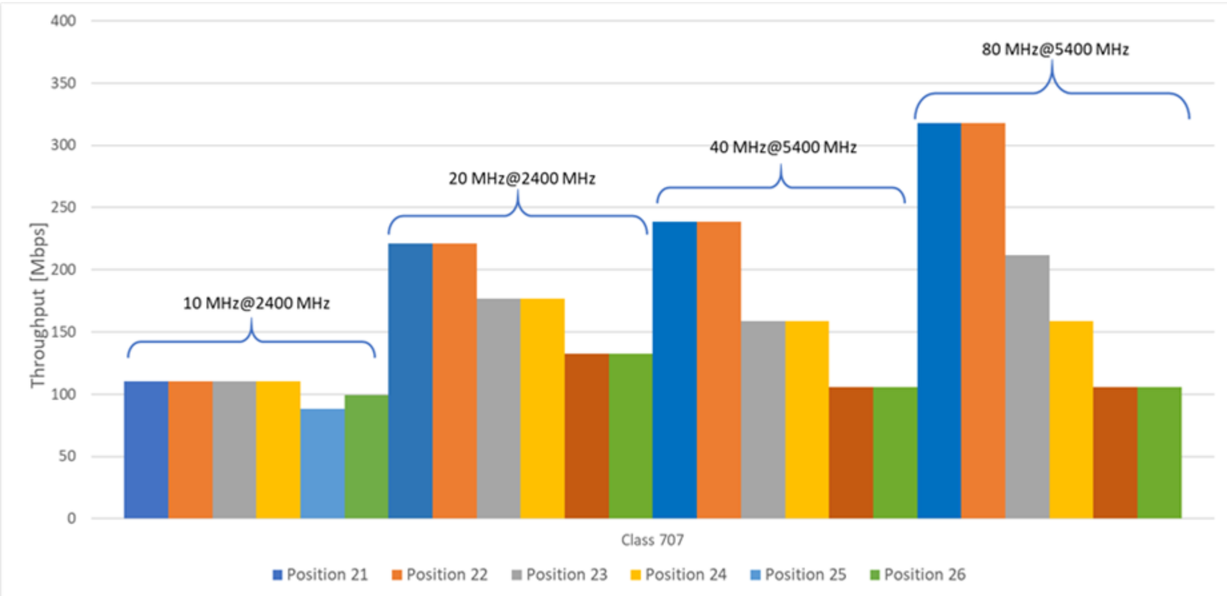
- 10MHz at 2,400 MHz
- 20MHz at 2,400 MHz
- 40MHz at 5,400 MHz
- 80MHz at 5,400 MHz

Figure 14a shows results for a BR MkIII trailer and Figure 14b for a Siemens Class 707 Desiro City.

The projections for both trains are very similar as VPL is side-stepped as the train-borne wifi gateway is assumed have a direct connection to an external antenna. They predict data capacities of at least 100MBps and up to 300Mbps at locations closest to the access point. The benefit of higher bandwidths fades with distance along the coach.



a) BR Mark III Trailer

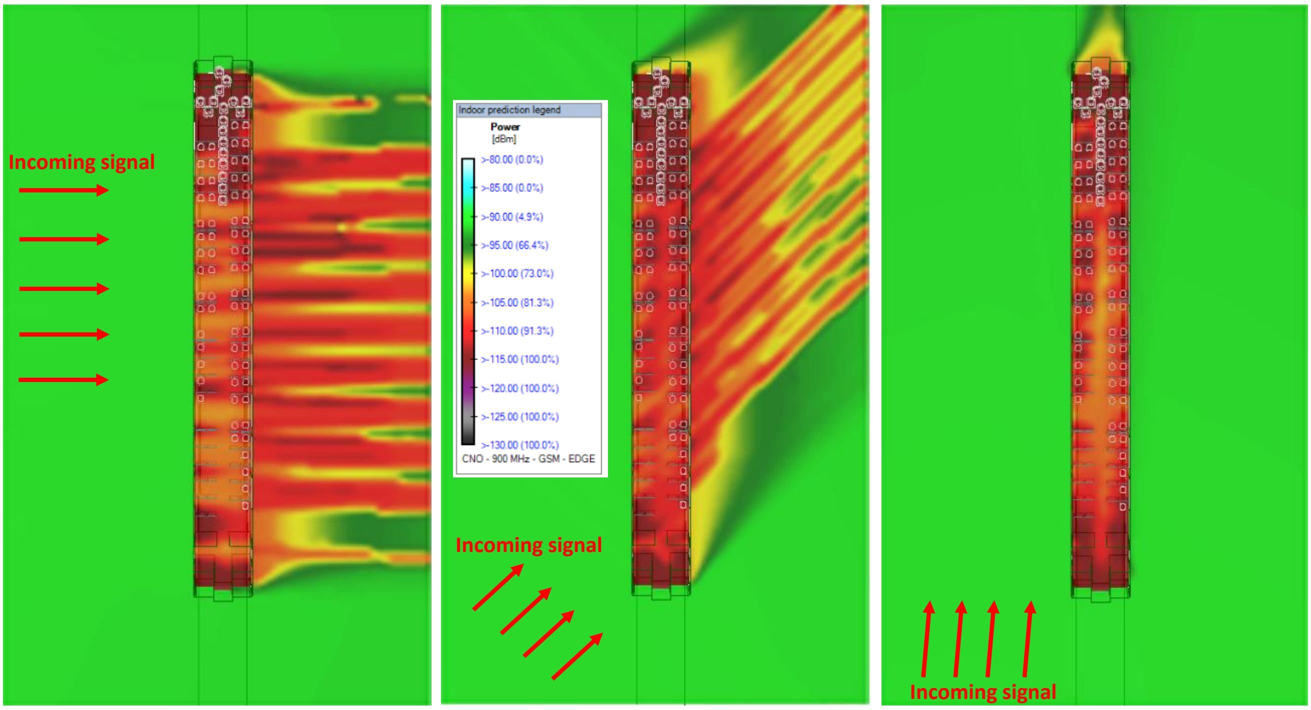


b) Siemens Class 707 Desiro City

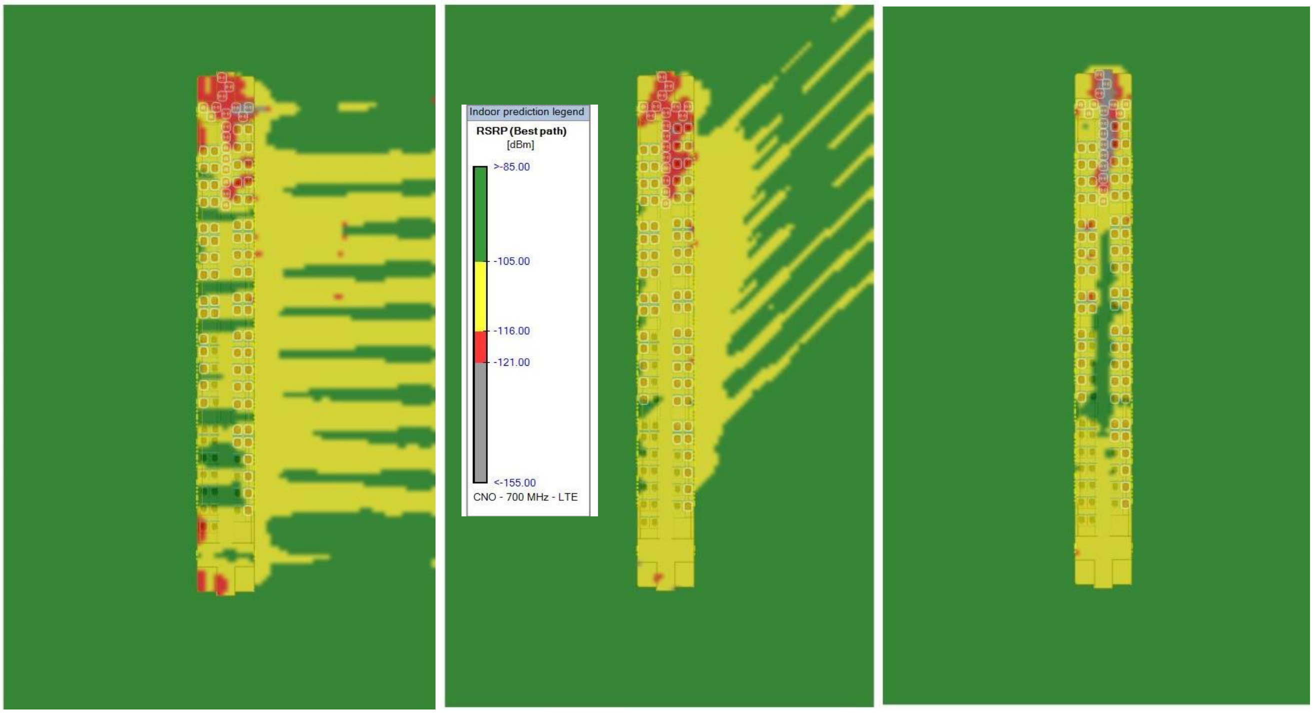
Figure 15 Modelled Wi-fi Data Capacity between train-borne gateway and passenger's mobile device

6.5 Mobile signal visualisation ‘heatmaps’

The modelling tool used is also able to generate ‘heat maps’ to visualize the variation of expected signal level through space. The modelling results are not definitive, so Figure 15 presents several ‘heat maps’ to illustrate the potential of the technique.



a) 2G (GSM) Voice signal propagation behaviour at 900 MHz and 90°, 45° and 5° incident angles. The signal outside the train carriage is -90 dBm (RxLev), while that inside the train body reflects the signal propagation inside and beyond the carriage



b) 4G (LTE) voice performance behaviour at 700 MHz. The signal outside the train is -90dBm RSRP (effectively 20dB greater than its 2G (GSM) equvalent)

Figure 16 ‘Heat Maps’ as tool to visualise the variation of mobile signal within a rail carriage

7 Main Findings and Recommendations

This section explains why the wide range of train signal attenuation means that the experience of passengers seeking a good direct mobile connection to their service provider will always be mixed.

7.1 A very wide range of train signal attenuation

Mobile operators typically allow for up to 25dB of signal attenuation between trackside and the passenger's mobile device on the train. This is generous compared with the 10dB assumed for brick-built domestic dwellings and cars. However, it is not enough to cope with the wide range of signal attenuation that rail passengers will experience. GB fleets can offer excellent connectivity to some passengers if they are on lightly-loaded trains or sitting next to a window, while denying any connectivity to others.

There are three main sources of signal attenuation between the exterior of the train and the built-in antennas within passenger's electronic devices:

- **Vehicle Penetration Loss** caused by train design (range 3dB to 28dB as tested, and reportedly worse for some trains)
- **User Body Loss** (UBL) caused by the way the mobile device is held and used (range 2dB to 20dB from literature review)
- **Crowding Body Loss** (CBL) is the screening effect of close crowding by other passengers and their belongings leading to large amounts of absorption (ranging from none to potentially 60dB in extreme circumstances from the literature review)

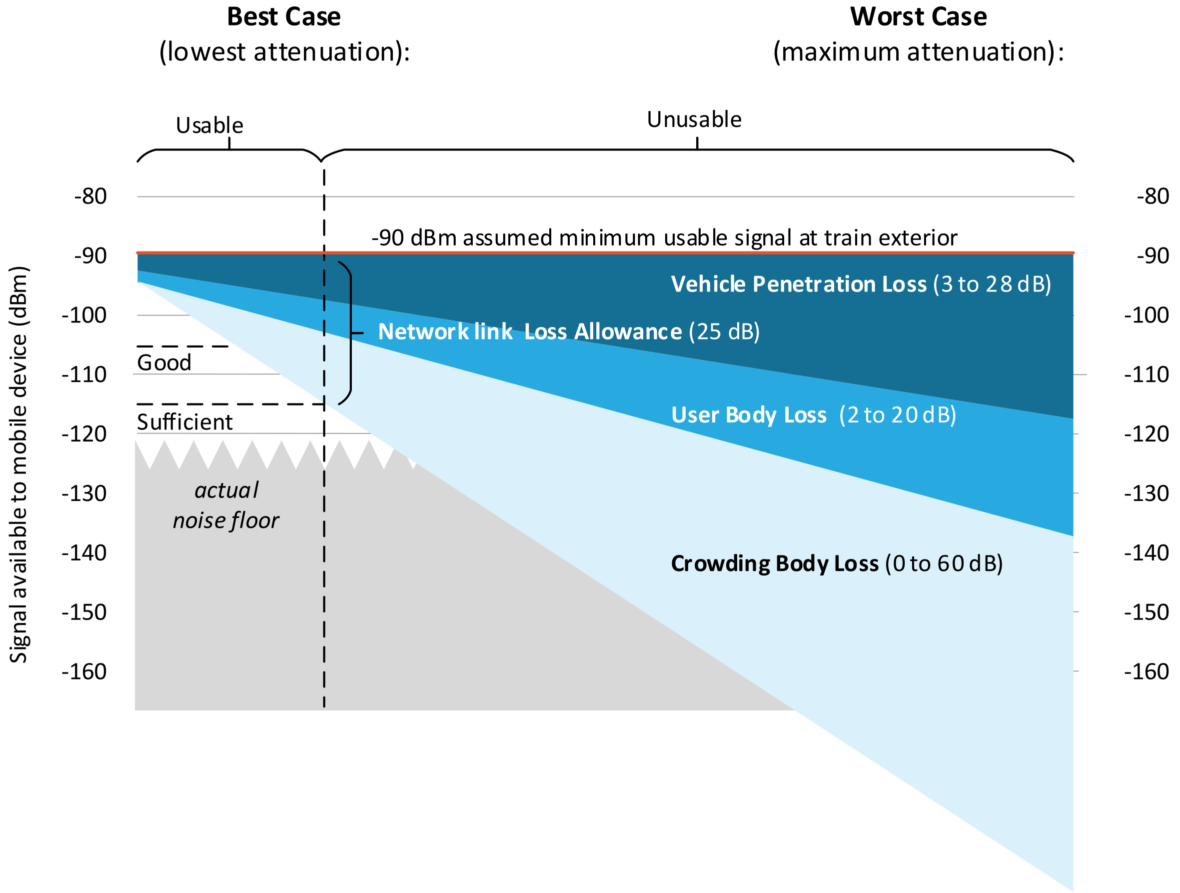


Figure 17 How wide range of train signal attenuation affects direct mobile connectivity

Figure 16 shows how these three sources of loss compound to a potential range between 5dB to in excess of 100dB and how this compares with the typical mobile operator provision. In this example, the trackside is irradiated with -90dBm of mobile signal.

If total signal attenuation is less than 25dB then at least -115dBm of signal power will reach the mobile device, good enough for a 4G/ 5G quality of service rated as 'sufficient' by Ofcom. The signal attenuation loss for passengers on lightly-loaded trains or close to windows could be well within this margin and offer excellent connectivity. However, other passengers on the same train or on trains with higher VPL characteristics would receive a signal too small to be usable.

7.2 Specify excellent RF propagation for glazing

The low VPL values of 3dB only occur through windows fitted with plain glass (toughened or laminated). This is the 'gold' standard for low RF-loss glazing.

As noted, the GB rail industry has typically fitted such window types for safety and operational reasons (Section 4.2.3). Other European railways have focused on improving thermal performance by fitting low emissivity glass that has the undesirable side-effect of increasing VPL by 20-30dB. The metallic coating reflects and blocks RF waves as well as infrared radiation from the sun (solar gain) or carriage heat loss. A technical solution has been developed to remove ~2.5% of the coating in a specific pattern that minimises the reflection of radio frequencies while retaining the thermal performance.

Train specifiers should ideally ensure that increasing environmental standards do not undermine RF propagation and seek at least $10m^2$ of bodyside glazing per carriage side.

7.3 Scope for other improvements to train design

Different suppliers of recent GB passenger fleets have offered designs based on 'monocoque' aluminium car bodies, usually, welded together, because they represent the best balance given the multiple requirements specified by the purchaser.

A side effect of these designs is that they can have an effect on mobile connectivity and the levels of losses. RF transmission through the car body is blocked by the 'Faraday cage' effect, whilst stricter thermal and acoustic insulation requirements also appear to increase Vehicle Penetration Loss as the result of tighter tolerances and improved sealing.

Suppliers are investigating the use of new composite materials, for example, as an alternative to aluminium for door panel leaves. Such materials may reduce VPL but not if they include a layer of aluminum foil in the composite as a heat reflector/radiator or water barrier. Some other candidate materials, such as carbon fibre, may be electrically conducting and have their own unique RF blocking characteristics.

7.4 Improve the strength and consistency of trackside signal along the line of route

The Mott MacDonald report of 2012 for Ofcom [29] identified four opportunities to improve to mobile connectivity:

1. Remove 'Not Spots' caused by poor rural coverage and lack of signal in-fill repeaters at deep cuttings and within tunnels – a serious problem that also affects the on-train wifi connectivity reliant today on external mobile network operator signals

2. Boost the trackside signal by 30-35dB to compensate for high train signal attenuation

3. Avoid metallic films on train windows that block RF

4. Encourage the development of train-borne gateways with external antennas to provide an intermediate signal relay between trackside transceivers and passenger mobile devices to 'sidestep' VPL and CBL

Whilst not directly related to carriage design, addressing points one and two through improving the strength and consistency of the external signal along the line of route would mitigate higher levels of VPL. It would also improve the consistency of the passenger experience whether using a mobile network connection or the on-train wifi.

Point three has already been noted in Section 4.2.3. Point 4 is discuss in the next section.

7.5 Train-borne gateways acting as intermediate signal relays or boosters

If the aim is to offer every rail passenger high quality wireless connectivity, then signal attenuation needs to be minimised or ideally eliminated between any external wireless network and the passenger's device and sufficient capacity provided.

External improvements in the RF link budget and availability of connectivity can clearly help as noted above. Addressing point 4, via train-borne gateways or small cells, in turn offers the ability to eliminate losses, allowing passengers to use their existing devices and services.

Such a train-borne gateway acts as an intermediate signal relay or booster/ repeater between the external network and passenger devices onboard the train (Figure 17). It may serve the whole train rake, an individual carriage, or unit, so must be able to adapt to likely train formations.

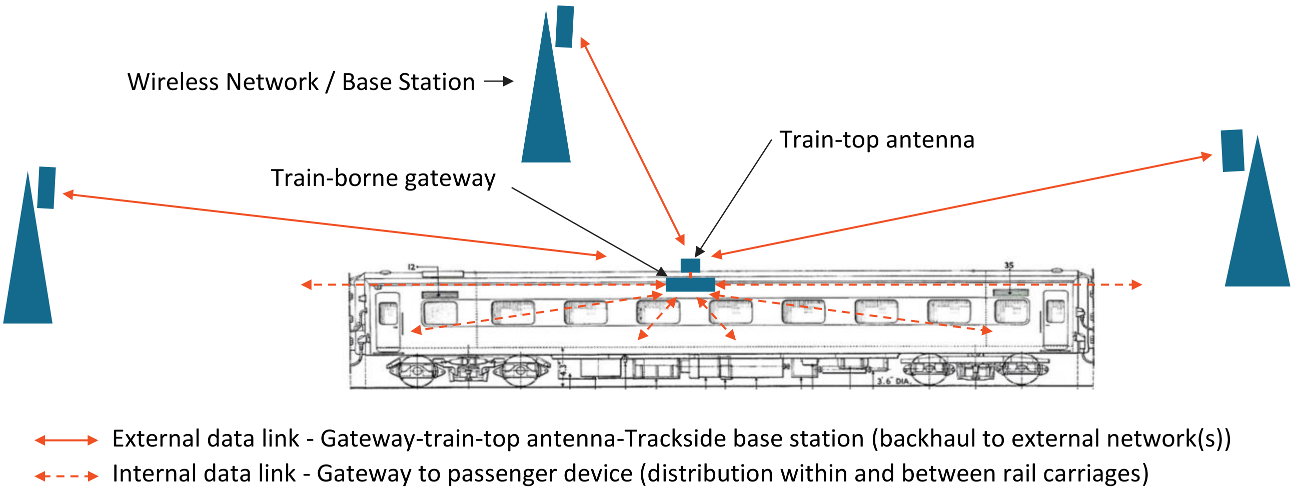


Figure 18 Train-borne gateway as intermediate signal relay or booster

As an intermediate signal relay, the gateway supports two wireless data links, one externally between the train and network (so called backhaul), and the other inside the carriage providing data connectivity between the gateway and each active passenger device.

A train-borne gateway eliminates the Vehicle Penetration Loss challenge and can also reduce onboard Crowding Body Loss effects since the external signals are normally re-radiated by the gateway through internal antennas in each carriage ceiling. Emerging multi-mobile network operator 4G and 5G small-cells could also provide a similar solution.

This is not a new idea. GB railways have been adopting and developing practical variants of this approach since the introduction of the Alstom Class 390 Pendolino to the West Coast Mainline in 2002, with operator-specific signal boosters (so-called Digital On Board Repeaters (D-OBR) 2006), plus several generations of on-train wifi gateways.

Today, all such approaches have their limitations given the need for the backhaul link to provide sufficient capacity to serve either passengers directly using their mobile subscription with one of the four main mobile network operators, or all passengers if using the on-train wifi. The same would be true for mounting small cells on trains.

The backhaul capacity required may be significant, hence the investment in additional base stations and/or trackside infrastructure.

However, there may be other ways of exploiting train gateways that reduce infrastructure costs while also improving mobile connectivity for passengers. For example, it could save infrastructure costs if designated trackside base stations were allowed to backhaul traffic on behalf of all mobile network operators with unbundling upstream at the gateways between the various mobile networks. The same base stations could also handle IP datastreams supporting wifi services.

If a technology agnostic train-borne gateway could be developed and associated backhaul approaches, it could serve all passengers with both mobile network operator services and wifi. Such an approach faces several challenges though worthy of further consideration:

- **Consistent signal coverage is still lacking,** with rapid infrastructure investment and delivery needed to remove ‘not spots’ – essential not just to improve both direct connectivity but also to take full advantage of investment in train-borne gateways and onboard wifi.

- **Surging demand:** the average passenger demand for data, especially on a fully loaded train, is growing exponentially from ~100Mbps per train in 2017 to 1.2 Gbps by 2025 (Ofcom) [6] and higher in the longer term. To deliver such speeds today is beyond the capabilities of traditional 4G cellular services.

- **Capacity supported by the train-borne gateway:** Single cellular 4G/ 5G channels offers 10-100Mbps per channel so carrier aggregation will be needed to meet anticipated levels. Whilst new mmWave spectrum allocations may offer channel capacities of 2-4 Gbps this is still highly proprietary compared to the tried and tested cellular model.

- **Economics:** The use of higher frequency and / or proprietary solutions with associated smaller cell ranges means that trackside infrastructure costs may be high.

- **Commercial appetite:** Mobile operators currently control the commercial relationship with their customers directly, and factor backhaul and operating costs in their operating model. Any model that changed this approach would need to carefully consider the allocation of benefits, costs and risks between the different entities in the delivery chain such as the mobile operators, train operators, rolling stock owners, even potentially Network Rail as infrastructure manager.

- **Train fitment:** The availability of spare space, weight restrictions, power and cabling are always important considerations for fitting new equipment to trains. Such fitment would also only make sense during major fleet refurbishments.

- **Compatibility with direct connectivity:** Any roll-out of ‘technology agnostic’ train-borne gateways is likely to take many years so will need to work alongside existing direct services. Market applications beyond rail that would broaden market demand for similar technology and hence reduce overall costs.

Mobile networks, wireless service providers and suppliers are also actively developing and planning new technologies to exploit new frequency spectrum and capacity including millimetre waves at 26 GHz and 60 GHz (with re-distribution via the in-carriage wifi), as well as investigating the use of train-borne 5G ‘small cells’. To date, none of these potential solutions for train connectivity are widely deployed other than as limited trials, and the supply chain for these solutions is limited at the time of writing this report.

7.6 Operational Solutions

Inform passengers where to expect the strongest signal within the train and along the line of route and update information as improvements come online. This will encourage passengers to use the capability available. Operators can rely on ‘first-come, first-served’ to regulate passenger behaviour, or remove the information if it becomes a problem.

Note Appendix 3 summarises some other sources identified during the literature review into mobile connectivity in France, China and Austria. They are of interest but not of direct relevance to the conclusions of this study.

8 Conclusions

This study is part of the DfT's objective to understand the practical and technical barriers to improving connectivity on the railway. Research highlights that rail passengers currently prefer direct access to their chosen mobile service provider even when wifi is available. The National Rail Passenger Survey by Transport Focus continues to highlight the generally poor perception of the availability of internet connectivity whilst travelling by rail.

The aim of this study was to investigate the contribution of passenger rail carriage design to radio frequency propagation as part of the wider mobile network and to understand the main attributes that could influence future train specification and design. It has fulfilled this aim through a combination of literature review, rolling stock fleet assessment, radio frequency VPL measurements on at least four rail carriages, RF link budget and performance calculations and complementary predictive radio frequency modelling.

Direct mobile connectivity will always be a major challenge for railways because of the very large range of train signal attenuation that can be experienced, far beyond the 25dB allowance made by mobile network operators.

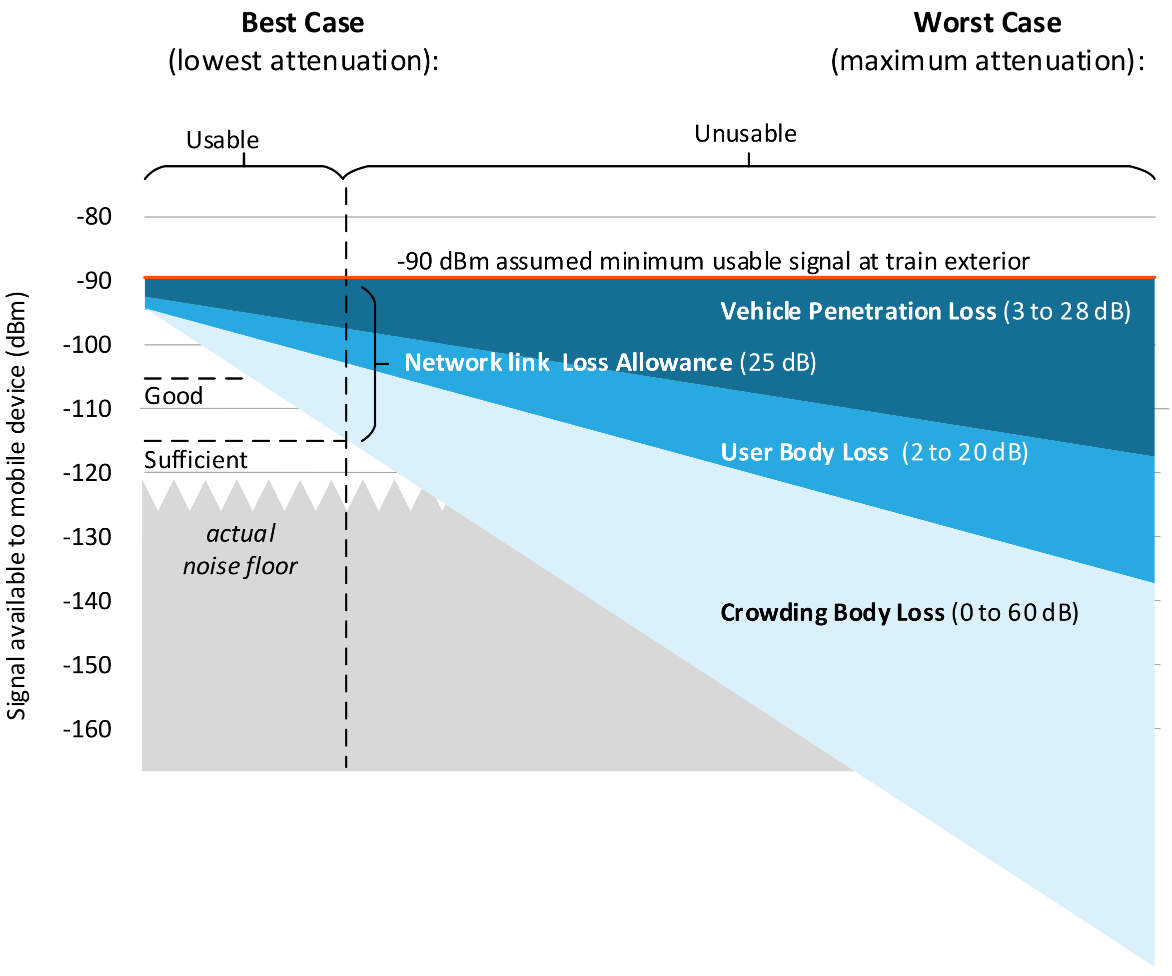


Figure 16 How wide range of train signal attenuation affects direct mobile connectivity

The study has highlighted that the combination of VPL, UBL and CBL can have a significant effect on a passenger's ability to make and receive voice calls and have a reasonable data connection. Whilst sitting close to a window can help, many factors are outside the passenger's control.

These findings reinforce the findings of the 'Not Spots' report by Mott MacDonald for Ofcom in 2012 [29] that recommended: infrastructure investment to deliver consistent signal strength along the line of route including rural areas, deep cuttings and tunnels, raising the signal strength by 30-35 dB to cancel out the VPL, avoidance of solid metallic coatings or films on train windows, and to sidestep VPL and CBL with train-borne gateways.

Mobile technology has advanced since 2012 with the advent of 4G/ 5G but so has demand for data capacity, soon 1 Gbps per train will be the minimum expected demand. Whilst careful specification of train construction and materials can help reduce the losses and hence improve passengers' mobile service quality, ultimately a combination of interventions may be required, including addressing external 'not spots', revising minimum external signal strength guidelines, through to building dedicated infrastructure and developing and deploying 'technology agnostic train-borne gateway solutions.

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)
AoA	Angle of Arrival
BEREC	Body of European Regulators for Electronic Communications
CA	Carrier Aggregation (available since 3G+)
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 and Sport
DfT	Department for Transport
DL	Down Link
D-OBR	Digital On-Board Repeater
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
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
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
FTN	Fixed Telecommunications Network

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
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
LOC & PAS TSI	European Union Technical Specification for Interoperability concerning locomotive and passenger rolling stock
LTE	Long Term Evolution [4G]
Mbps	Mega bits per second (1,000,000 bits of data per second)
MIMO	Multiple Input Multiple Output [antennas]
MM	Millimetre Waves. Extremely high frequency electromagnetic radiation with wavelengths of the order of millimetres (for example, wavelength= 5mm @ 60GHz, 11.5mm@ 26GHz). Also known as V-band.
MNO	Mobile Network Operator
MSC	Mobile Switching Centre
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
OTA	Over the Air
Pax	Passengers
PRB	Physical Resource Block
PTS	Personal Track Safety
RBE	Risk-based Evaluation
RIDC	[NR] Rail Innovation and Development Centres providing train test tracks at: - Melton Mowbray, Leicestershire (high speed, electrified - 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
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 and Standards Board
RSSI	Received Signal Strength Indicator
RxLev	Received power Level (for GSM)
RX	Receive
SCS	Sub-Carrier Spacing
SE	Spectral Efficiency
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
TX	Transmit
TOC	Train Operating Company
TRP	Total Radiated Power
TIS	Total Isotropic Sensitivity
TX	Transmit
UE	User Equipment
UIC	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

References

Reference	Description
[1]	'Connected Future', National Infrastructure Commission, 2016 https://nic.org.uk/app/uploads/Connected-Future-Report.pdf
[2]	'Connected Future – getting back on track – a review of government progress delivering mobile connectivity on roads and railways' National Infrastructure Commission, February 2020 https://nic.org.uk/studies-reports/connected-future/connected-future-getting-back-on-track/ https://nic.org.uk/news/passengers-facing-second-class-mobile-connectivity-on-uk-rail-network/
[3]	'First Group and Blue Wireless partnering to provide superfast 5G wifi on trains', 25th February 2019, Press Release, First Group South Western Railway franchise, https://www.firstgroupplc.com/news-and-media/latest-news/2019/25-02-19.aspx
[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/
[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
[6]	'Advice to government on spectrum suitable for improving rail passenger access to data services – update to 2018 rail connectivity advice', Ofcom, June 2020 https://www.ofcom.org.uk/__data/assets/pdf_file/0028/199018/rail-connectivity-advice-june-20.pdf
[7]	'Connected Nations 2020 UK report, Ofcom, 17th December 2020 https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2020 'Connected Nations 2020 UK report, Ofcom, 17th December 2020: Annex A Methodology https://www.ofcom.org.uk/__data/assets/pdf_file/0019/209440/connected-nations-2020-methodology.pdf
[8]	'Connected Nations 2019 Data Dashboard' (MS Excel Spreadsheet) https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2019/data-downloads [Same location for mobile signal strength measurement data from NR 'yellow' engineering trains at 2G, 3G and 4G]
[9]	'Common Position on information to consumers on mobile coverage', Body of European Regulators for Electronic Communications (BEREC), BoR (17) 186, 2017 https://berec.europa.eu/eng/document_register/subject_matter/berec/public_consultations/7300-draft-berec-preliminary-report-in-view-of-a-common-position-on-monitoring-mobile-coverage
[10]	'In-car Mobile Signal Attenuation Measurements', LSTelcom and Siroda commissioned by Ofcom, 8th October 2017 https://www.ofcom.org.uk/__data/assets/pdf_file/0019/108127/in-car-mobile-signal-attenuation-report.pdf
[11]	'Characterization of Vehicle Penetration Loss at wireless communication frequencies', Virk et al, IEEE 8th European Conference on Antennas and Propagation (EuCAP), 2014, The Hague, Netherlands, pp 234-238 https://ur.booksc.org/book/30901073/d753a5
[12]	'Award of the 700 MHz and 3.6-3.8 GHz spectrum bands:', Ofcom, 13th March 2020 https://www.ofcom.org.uk/__data/assets/pdf_file/0019/192412/information-memorandum-award-700mhz-3.6-3.8ghz-spectrum.pdf Annexes 5-18 – supporting information: https://www.ofcom.org.uk/__data/assets/pdf_file/0021/130737/Annexes-5-18-supporting-information.pdf

[13] ‘Passenger rail usage 2020-21 Q2’, Office of Rail and Road, 10th December 2020 https://dataportal.orr.gov.uk/statistics/usage/passenger-rail-usage/

[14] *[Confidential]* ‘Class 374 at St Pancras International station - Penetration Test Report V1.0’, confidential, EE 2016

[15] *[Confidential]* ‘MS1 & DPT1 at St Pancras International station - Penetration Test Report V1.0’, EE 2016

[16] ‘User influence on the mean effective gain for data mode operation of mobile handsets’, J. Ø. Nielsen et al., European Conference on Antennas and Propagation, 2012, pp. 2759-2763 https://www.researchgate.net/publication/261237875_User_influence_on_the_mean_effective_gain_for_data_mode_operation_of_mobile_handsets

[17] ‘Mapping of microwave power transmitted through the human thorax’, I. Yamaura, , Proceedings of the IEEE, vol. 67, no. 8, pp. 1170-1171, Aug. 1979 https://ieeexplore.ieee.org/document/1455687

[18] ‘Measurements of 1.8 - 2.7-Ghz Microwave Attenuation in the Human Torso’, I. Yamaura, , IEEE Transactions on Microwave Theory and Techniques, vol. 25, no. 8, pp. 707-710, Aug. 1977

[19] ‘Mobile Phone Antenna Performance 2018’, Pedersen, G. F. (2018).. Institut for Elektroniske Systemer, Aalborg Universitet. https://vbn.aau.dk/en/publications/mobile-phone-antenna-performance-2018

[20] ‘Mobile Handset Testing – a Report for Ofcom’, November 2015 UL inc (commercial off-shoot of Underwriters Laboratories) https://www.ofcom.org.uk/__data/assets/pdf_file/0015/72231/mobile_handset_testing_1v01.pdf

[21] LOC & PAS TSI: ‘…Concerning a technical specification for interoperability relating to the ‘rolling stock —locomotives and passenger rolling stock’ subsystem of the rail system in the European Union’, European Union Commission Regulation No 1302/2014, 18 November 2014 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R1302&from=EN
Further guidance and related documents may be found at: https://www.era.europa.eu/activities/technical-specifications-interoperability_en

[22] ‘Rail Vehicle Structures and Passive Safety’, GM/RT 2100, Issue 6, Rail Safety & Standards Board, March 2020 https://www.rssb.co.uk/standards-catalogue/CatalogueItem/GMRT2100-Iss-6

[23] ‘Rail Vehicle Structures’, RIS-2780-RST Issue 1, Rail Safety & Standards Board, March 2020 https://www.rssb.co.uk/standards-catalogue/CatalogueItem/RIS-2780-RST-Iss-1

[24] ‘Requirements for Train Windows on Passenger Carrying Rail Vehicles (T424)’, RSSB R&D Programme: Research Brief, 19th December 2005 https://www.railwaysarchive.co.uk/documents/RSSB_Windows2005.pdf

[25] ‘FLACHGLASconnect – Functional insulating glass, permeable by mobile radio waves’, Brochure https://www.flachglas.de/fileadmin/user_upload/download/Mediathek/Broschueren/Broschueren_NEU/FLAG_Broschuere-FLAGconnect_Hochbau_online.pdf

[26] ‘Metal-coated windowpane, particularly for rail vehicles’ , Mayer et al, International Patent Application EP1471824.4A, 7th April 2014 https://patents.google.com/patent/EP2984707A1/en

[27] ‘3M Commercial Graphics Scotchgard™ Graphic and Surface Protection Films https://multimedia.3m.com/mws/media/799349O/product-card-8991-8993-8995.pdf

[28] 3M™ Prestige Sun Control Films For perfect sun protection and optimal indoor climate. https://multimedia.3m.com/mws/media/1579347O/brochure-sun-control-prestige-window-films.pdf

[29] ‘Rail “Not-spots” -Technical Solutions & Practical Issues’, Mott MacDonald, 2012 https://www.ofcom.org.uk/__data/assets/pdf_file/0018/50085/rail-not-spots.pdf

[30] ‘Development of a cross-industry business case and spectrum valuation for wireless telecommunications, Mott Macdonald for RSSB Study T911, March 2009

[31] ‘Mobile communications strategy including : ‘Operational communications Spectrum position paper’, and ‘Work Package 3: Operational communications Connected services framework – Spectrum position paper ’RSSB Study T964, March 2012
https://www.rssb.co.uk/research-catalogue/CatalogueItem/T964

[32] ‘Connected Train and Customer Communications: Rail and Digital Industry Roadmap’, RSSB Study T1138, 2018
https://www.rssb.co.uk/en/research-catalogue/CatalogueItem/T1138

[33] ‘Cities Project’, Analysys Mason final report 37110-282 for Ofcom, 8th July 2013
https://www.ofcom.org.uk/__data/assets/pdf_file/0019/24166/cities-report.pdf

[34] ‘Test reports - Confrontation between experimental and numerical results: Analysis of the attenuation of the wifi signals inside and outside a railway vehicle’, Virginie Deniau, HAL Open Access Archive reference: hal-00544468, 16th June 2009
https://hal.archives-ouvertes.fr/hal-00544468/document

[35] ‘Broadband wireless channel measurements for high speed trains’, Kaltenberger et al, IEEE International Conference on Communications (ICC), 2015, pp 2620-2625
https://www.eurecom.fr/~arvanita/Trains.pdf

[36] ‘Challenges toward wireless communications for high-speed railway’, B. Ai et al, IEEE Trans. Intell. Transp. Syst., vol. 15, no. 5, pp. 2143-2158, October 2014
https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6808529

[37] ‘Radio Wave Propagation Scene Partitioning for High Speed Rails’, B. Ai et al, Hindawi International Journal of Antennas and Propagation, 2012, Article ID 815232, 7 pages, 2012.
https://www.hindawi.com/journals/ijap/2012/815232/

[38] ‘Channel Measurements and Models for High-Speed Train Communication Systems: A Survey’, Wang et al, IEEE Communications Surveys & Tutorials, 18(2) pages 974-987, Second quarter 2016, doi: 10.1109/COMST.2015.2508442
https://ieeexplore.ieee.org/document/7355284

[39] ‘Wireless Communications in Smart Rail Transportation Systems’, Briso-Rodríguez, Guan et al, Hindawi Wireless Communications and Mobile Computing, 2017 Article ID 6802027
https://doi.org/10.1155/2017/6802027
https://www.hindawi.com/journals/wcmc/2017/6802027/

[40] ‘Providing Current and Future Cellular Services to High Speed Trains’, Martin Klaus Müller, Martin Taranetz and Markus Rupp, IEEE Communications Magazine, 2015, 53(10), pp 96-101
https://arxiv.org/pdf/1505.04557.pdf

[41] ‘A Survey of Channel Measurements and Models for Current and Future Railway Communication Systems’, Unterhuber et al, Mobile Information Systems, vol. 2016, Article ID 7308604, 14 pages, 2016. https://doi.org/10.1155/2016/7308604
https://www.hindawi.com/journals/misy/2016/7308604/

[42] ‘Distributed Measurements of the Penetration Loss of Railroad Cars’, Lerch et al (various Austrian organisations), IEEE 86th Vehicular Technology Conference (VTC-Fall), 2017, Toronto
https://publik.tuwien.ac.at/files/publik_260969.pdf

[43] ‘Evaluation of Vehicle Penetration Loss at Wireless communication Frequencies’, Tanghe et al, IEEE transactions on vehicular technology, 2008, 57 (4) p2036-2041
https://biblio.ugent.be/publication/672073, https://ieeexplore.ieee.org/document/4382920

Appendices

Appendix 1 Passenger journeys by carriage type

Train Name	Number of Vehicles	Manufacturer	% Vehicles	% Passenger Journeys
A-Train	1197	Hitachi	9%	5%
Aventra	1625	Bombardier	13%	17%
Civity	528	CAF	4%	5%
Class 121	2	Pressed Steel	0%	0%
Class 165	299	BREL	2%	3%
Class 230	9	Vivarail	0%	0%
Class 313 1972 PEP	189	BREL	1%	2%
Class 319	128	BREL	1%	2%
Class 333	64	Siemens	0%	1%
Class 455 1972 PEP	184	BREL	1%	2%
Class 483	10	Metro-Cammell	0%	0%
Coradia	70	Alstom	1%	0%
Desiro	1020	Siemens	8%	7%
Desiro City	1290	Siemens	10%	14%
Electrostar	2263	Bombardier	18%	14%
Express Sprinter	461	BREL	4%	2%
Flirt	282	Stadler	2%	2%
Javelin	174	Hitachi	1%	1%
Mark 5A Carriage	65	CAF	1%	0%
Mark III Carriage	267	BREL	2%	1%
Mark IV Carriage	54	BREL	0%	0%
Networker	674	Metro-Cammell	5%	10%
Networker Express	76	ABB	1%	1%
Pacer	60	BREL	0%	1%
Pendolino	574	Alstom	4%	2%
Sprinter	234	BREL	2%	1%
Super Sprinter	153	BREL	1%	2%
Super Voyager	357	Bombardier	3%	2%
Thames Turbos	63	ABB	0%	0%
Turbostar	271	Bombardier	2%	1%
Voyager	136	Bombardier	1%	1%
Wessex Electrics	90	BREL	1%	1%
Totals	***12,869***		***100%***	

Table 9 Approximate breakdown of passenger carriage types by number and passenger journeys

Appendix 2
Modelling and Test Assumptions

App 2.1 Mobile Connectivity Configurations

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

Table 10 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 11 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 12 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 13 Resource Blocks available for use (4G/ 5G)

Technology	Highly 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

Table 14 Quality of Service Indicators based on modelled signal power
Source: Ofcom 2019 [8]
Notes:
a) signal power metrics are 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

App 2.2 Test and Modelling Equations

Formula used to calculate the signal attenuation taking into account multi-path fading, transmit power, path loss and other losses include :

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - L_{FSL} \qquad \textbf{(1)}$$

P_{Rx}	Received Power	(dBm)
P_{Tx}	Transmitted Power Output	(dBm)
G_{Tx}	Transmitter Antenna Gain	(dBi)
G_{Rx}	Receiver Antenna Gain	(dBi)
L_{FSL}	Free space loss:	

$$L_{FSL} = 92.45 + 20\,log_{10}(\,f_{GHz}\,) + 20\,log_{10}(\,d_{km}\,) \qquad \textbf{(2)}$$

f_{GHz}	Frequency	(GHz)
d_{km}	Distance	(km)

The in-train received signal from the outside-train signal is calculated as:

$$P_{Rx,\ In\text{-}train} = P_{Rx,\ Outside} + G_{Rx} - L_{Train} - L_{Body} \qquad \textbf{(3)}$$

$P_{Rx,\ In\text{-}train}$	signal power metric: received signal level (2G), RSCP CPI (3G) or RSRP (4G/ 5G)
G_{Rx}	antenna gain of the receiver
L_{Train}	Vehicle Penetration Loss
L_{Body}	User and Crowding Body Loss
$P_{Rx,\ Outside}$	external signal power metric irradiating train is set to -90 dBm.

Appendix 3
Other sources

There have been many previous studies to improve mobile connectivity to passengers on trains. Table 15 raises general points from earlier studies. Table 16 presents other previous attempts to determine Vehicle Penetration Loss.

Context	Year/ Source	Comments
French Railways	2010, Deniau et al [34]	Investigation of wifi installation performance and electromagnetic compatibility with similar installations on adjacent TGV trains operating at 2.45GHz and 5GHz (802.11g access points with inter-car bridges to 802.11a) signal from an actual access point reduced by 17dB. The carriage was stripped of seats and most other fixtures and fittings. When the test antennas were used this increased to 25-30dB. VPL measurement was from the ceiling access point to a passing train -60-70dB for the test antennas, 32 to 52dB for the actual access point.
	2015, Kaltenberger et al [35]	Serious attempt to analyse, design and measure systems that maximise track-train data capacity on high speed trains using MIMO antennas on train and ground. Observed Doppler shift including the effect of reflections from overhead line gantries.
China High Speed Railways	2012-14, China, Ai et al [36, 37]	Review of challenges of providing mobile connectivity to very high-speed railways (sub-2GHz).
	2016, [38], Wang et al	
	2017, [39], Briso-Rodriguez, Guan et al	Whole system review of state-of-the-art technologies and constraints to deliver mobile connectivity.
Austria, Institute of Telecommunications	2015 Müller et al [40]	Discussion of relative merits of direct connectivity and train-borne gateways. Note high doppler shifts at 350km/h,
	2016, [28], Wang et al	
	2016, Unterhuber et al [41]	

Table 15 Range of Vehicle Penetration Loss (literature review)

Vehicle Penetration Loss (dB)	Year/ Source	Comments
3-10dB (window loss)	2017, Austria. Lerch et al [42]	Results affected by metallic coatings (see Section 4.2.3). Describes measurement setup. These results may not be for plain glass.
14-54dB	2016-17, EE for High Speed 1 Confidential [14, 15]	Measurements at St Pancras International on Siemens Class 374 Eurostar e320 train and Hitachi Class 395 140mph EMU (see Figure 2i-j). This study only has access to the headline numbers, not the underlying assumptions.
3 dB (plain glass) 6.6 dB (‘window film’) 20.7 dB (aluminium foil)	2014 Virk et al [11]	Vehicle Penetration Loss measurements on road cars – average across all frequency bands.
15-25 dB	2012, Mott McDonald for Ofcom [29]	Similar to measurements recorded by this study. Also assumes only up to 10dB for User and Crowding Body Loss.
	2008 [43]	Not viewed.

Table 16 Range of Vehicle Penetration Loss (literature review)

The information in Table 16 was either not backed by measurement, not directly linked to mobile connectivity, or it was unclear if metallic coatings on bodyside windows may have skewed the results.

End notes supporting the Executive Summary:

[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] [29] ‘Rail “Not-spots” -Technical Solutions & Practical Issues’, Mott MacDonald, 2012 https://www.ofcom.org.uk/__data/assets/pdf_file/0018/50085/rail-not-spots.pdf