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Coverage thresholds for 5G services

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About Plum

Plum offers strategy, policy and regulatory advice on telecoms, spectrum, online and audio-visual media issues. We draw on economics and engineering, our knowledge of the sector and our clients' understanding and perspective to shape and respond to convergence.

About this study

This study for ComReg provides a review of current information regarding the definition of coverage thresholds for 5G services and makes recommendations of appropriate limits for use in ComReg's consumer-facing coverage mapping.

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ComReg currently provide a consumer-focussed online outdoor coverage mapping tool for mobile services. At present, this popular facility, which receives around 8,000 visits each week, provides information on the geographical outdoor coverage of 2G, 3G and 4G services.

With the launch of 5G services in Ireland, there will be a need to extend the functionality of the mapping tool to include 5G. This study by Plum examines issues relating to the choice of appropriate signal thresholds for use in 5G outdoor coverage mapping and makes recommendations for suitable values.

1 Introduction to mobile coverage mapping

ComReg provides, via its website, mobile coverage mapping data to enable consumers to better understand the levels of outdoor coverage across Ireland in respect of mobile network operators (MNOs) and mobile virtual network operators (MVNOs).

The predictions made available online are generated using the Forsk 'Atoll' radio planning tool, together with the 'Crosswave' radio propagation model by Orange labs. The predictions are based on detailed network data submitted by the MNOs.

The online predictions are presented to the public in terms of categories of coverage levels, rather than as technical threshold levels. For 4G, the following categorisation descriptions are used:

- Very Good: Strong signal strength with maximum data speeds.
- Good: Strong signal strength with good data speeds
- Fair: Fast and reliable data speeds maybe attained, but marginal data speeds with data dropouts are possible at weaker signal levels.
- Fringe: Disconnections likely to occur.
- No Coverage: Likely to have no coverage in this area.

The mapping between these coverage category levels and technical thresholds for the currently covered services is set out in Table 1 below.

Table 1: 2G, 3G and 4G technical thresholds per coverage categorisation on ComReg's mapping tool

Coverage Categorisation	4G (RSRP[1],dBm)	3G (RSCP[2], dBm)	2G (RxLEV[3], dBm)
Very good	-85 ≤ X	-75 ≤ X	-71 ≤ X
Good	-95 ≤ X <- 85	-85 ≤ X < -75	-81 ≤ X < -71
Fair	-105 ≤ X <- 95	-95 ≤ X < -85	-91 ≤ X < -81
Fringe	-115 ≤ X <- 105	-105 ≤ x < -95	-101 ≤ X < -91
No coverage	X < -115	X < -105	X < -101

At present, the coverage of 2G, 3G and 4G networks is indicated within the online service. Now that the three MNOs have started to roll-out 5G coverage, it is appropriate to consider adding predictions of these services to the online tool.

This will require the definition of thresholds for 5G services for each of the coverage categories in Table 1.

[1] Reference Signal Received Power
[2] Received Signal Code Power
[3] Received Signal Level

The thresholds, as is the case with the 2G, 3G, 4G technology will apply to **outdoor coverage only** and need to be supported by a rationale for the definition of the specific ranges of signal strength associated with each category. This report provides that information.

2 Review of limits assumed globally for 4G/LTE services

2.1 Defining cellular coverage limits

Defining the coverage limits for early cellular systems was relatively straightforward, as systems such as GSM were constrained to use fixed data rates and modulation and coding schemes. User equipment (UE) antennas also tended to offer more predictable performance, often covering a single band and being external to the handset.

With the introduction of 2.5G and 3G systems, the growing importance of data rather than speech, new frequency bands and different approaches to handset design, the definition of coverage limits became a much more complicated statistical problem. In many cases, and particularly for public-facing data, these coverage statistics need to be condensed to a single figure and an apparently well-defined contour. Factors that need to be considered in this definition include:

- Modulation scheme(s)
- Coding rate(s)
- UE antenna gain
- Receiver noise performance
- Required availability
- Local fading characteristics (multipath & clutter)
- Inter and intra network interference
- Buffering and latency requirements of different applications

Many of these factors can only be characterised statistically or empirically, and some may be commercially confidential.

2.2 Existing national 4G limits

In December 2018, the Body of European Regulators for Electronic Communications (BEREC) published a useful summary of existing coverage thresholds adopted in different European countries, with the aim of "*fostering a consistent approach on how mobile coverage information can be made available and understandable among NRAs and to the public throughout Europe*". [4]

It should be noted the 4G thresholds summarised in the BEREC document make a variety of assumptions regarding technical characteristics, such as carrier bandwidth, and are not, therefore, always directly comparable. An impression of the different 4G threshold values adopted can, however, be seen in the histogram of Figure 2.1 below.

[4] BEREC Common Position on information to consumers on mobile coverage (europa.eu)

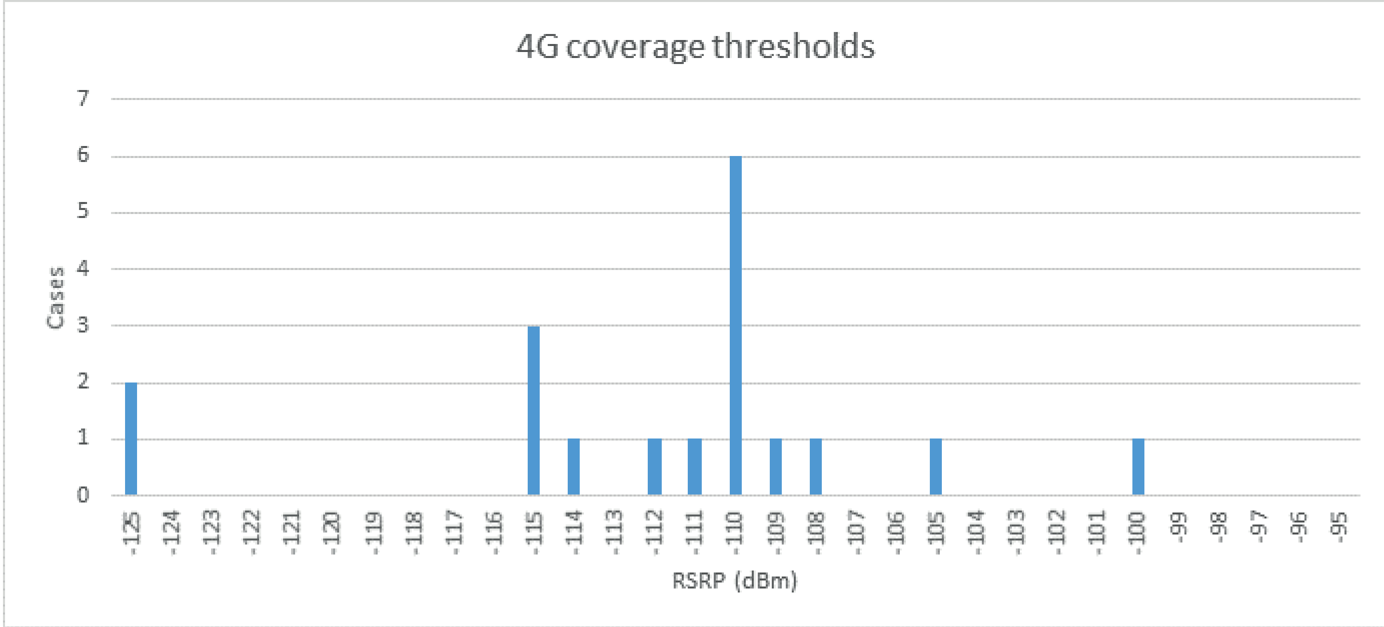


Figure 2.1: European LTE coverage thresholds (lowest level)

Where an administration quotes several thresholds, only the lowest is plotted in the figure above. Germany is the only country to differentiate by bandwidth (10, 15 and 20 MHz) and the Czech Republic is currently the only country to do so by frequency (800, 1800, 2100 and 2600 MHz).

The lowest values (-125dBm), from Portugal and Greece, and the highest (-100 dBm) from Iceland[5] appear to be outliers. It is reassuring to note that the Irish 'Fringe' range embraces all other stated thresholds.

The BEREC report also recommends that, 'd*ue to large variations in handset RF performance*', coverage predictions should be calculated assuming a 'neutral receiving device' with an antenna gain of 0 dBi at 1.5m height above ground. The BEREC report also notes that the use of a neutral receiving device *'does not stop NRAs from accounting for handset gain/loss being on their maps'*.

More recently, in March 2020, a BEREC consultation on 5G coverage limits concluded that "*it would be too early for BEREC to set out a policy objective to provide harmonised information on 5G coverage and QoS aspects of networks*" and the current thinking of BEREC is that *"it should adopt a wait and see approach"* potentially revisiting this topic in two or three years' time following the *"deployment of one or two use cases"*.[6]

It is also noteworthy that responses to this consultation by MNOs elsewhere in Europe were generally of the opinion that (i) there was insufficient experience of real-world 5G network performance to set thresholds and (ii) that MNOs would, in any case, be better placed to do so than regulators, owing to their detailed knowledge of the systems involved.

[5] For 'Rural' coverage
[6] Feasibility study on development of coverage information for 5G deployments (europa.eu)

3 Technology differences between 4G & 5G

3.1 Introduction

4G/LTE[7] coverage limits are generally expressed in terms of a 'Reference Signal Received Power' (RSRP), while those for 5G/NR[8] use a 'Synchronisation Signal Reference Signal Received Power' (SS-RSRP).

The relationship of these parameters to the overall LTE and NR signal structure is summarised briefly in this section.

3.2 LTE Physical layer

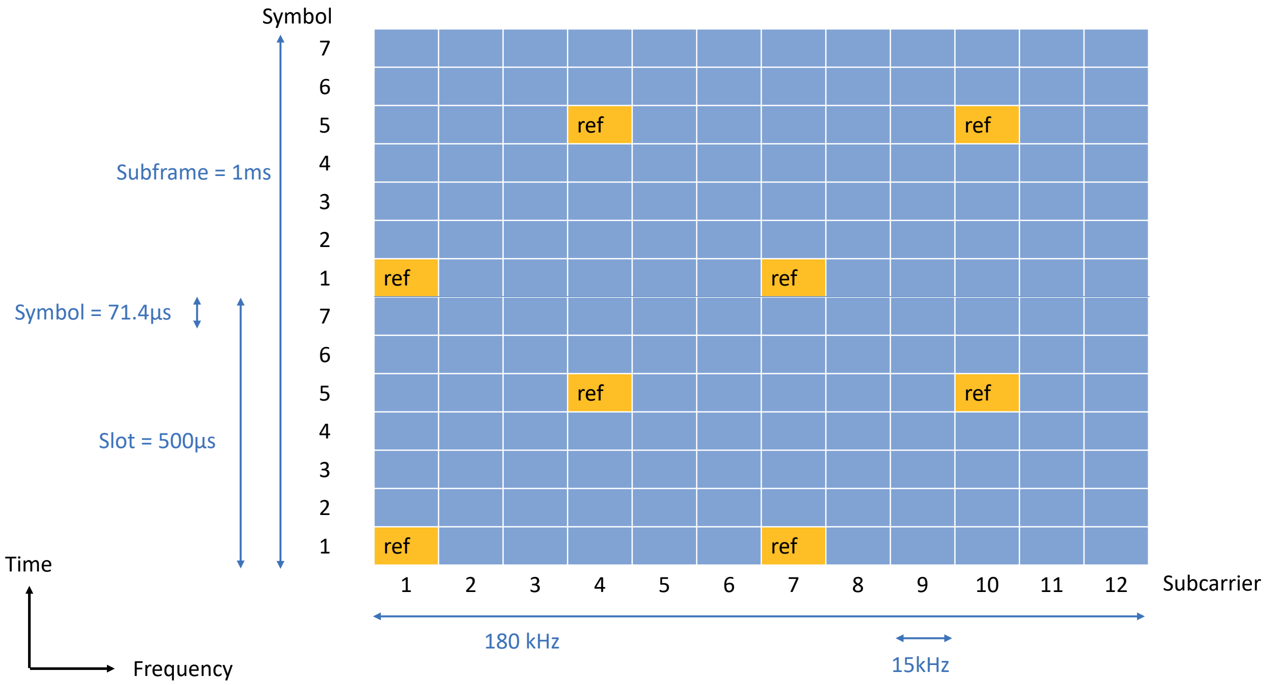
The LTE downlink uses Orthogonal Frequency Division Multiple Access (OFDMA), with a subcarrier spacing of 15 kHz and a useful symbol time of 66.7µs. The cyclic prefix (CP) is normally ~5µs, but an extended CP of 16.7µs is available for use in very large rural cells with significant multipath, or for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

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

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

[7] LTE = 'Long Term Evolution", the 4G technical standard.
[8] NR = 'New radio', the 5G technical standard.

Figure 3.1: LTE Resource Blocks (1 RB = 12 subcarriers x 7 symbols)



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

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

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

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

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

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

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

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

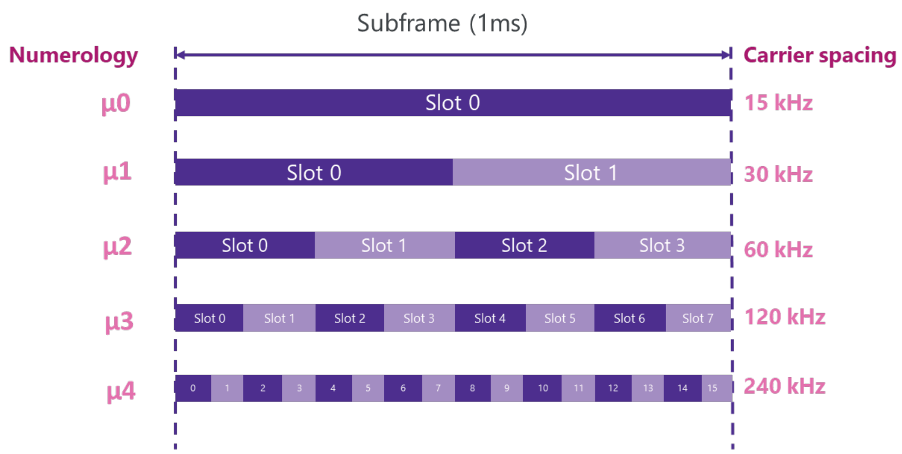
3.3 NR Physical layer

The NR physical layer introduces a number of significant changes with respect to LTE:

- A more flexible numerology, allowing for different subcarrier spacing/symbol duration and the granularity of slots within subframes. The particular numerology in use is indicated by the parameter µ **where,** for example µ=0 indicates a 15 kHz subcarrier spacing and µ=1 a 30 kHz spacing. The use of higher µ values allows for greater temporal flexibility i.e. shorter slots for dynamic assignment) at the cost of some spectrum efficiency.

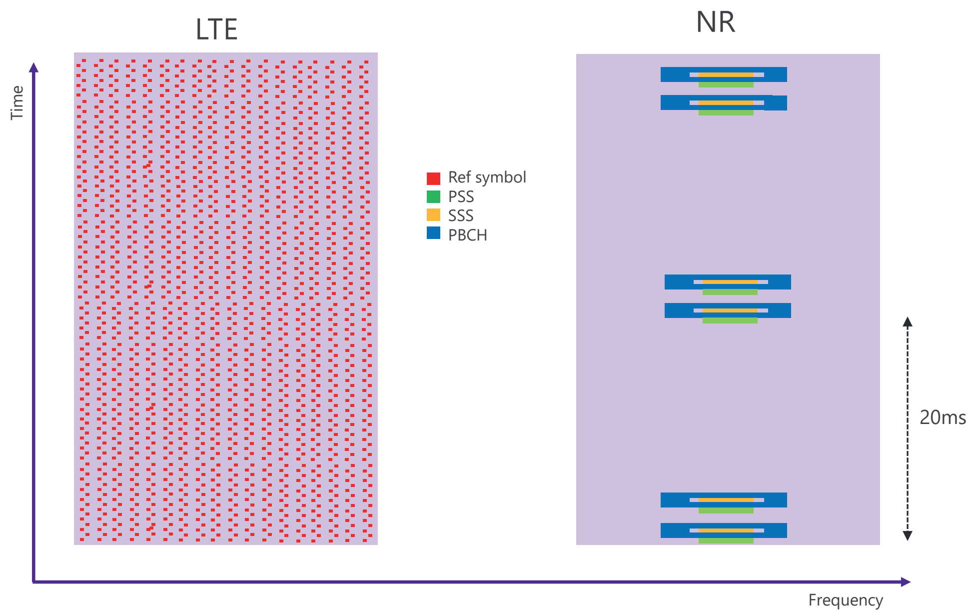
- A fundamentally beam-based approach in which the concept of 'cells' and 'sectors have little relevance.

Figure 3.2: Numerology in NR



The focus on beams requires a revised strategy for reference signals. These are now transmitted within a dedicated 'synchronisation signal block (SSB)' of four BPSK symbols, rather than being scattered throughout the data channel.

Figure 3.3: Sketch of reference signals in LTE and NR



Separate SSB blocks are transmitted for up to 4 beams (<3 GHz), 8 beams (3-6 GHz) or 64 beams (>6 GHz) in each Resource Block. These multiple bursts of four symbols are sent with a 20ms periodicity. A user terminal will identify the burst with the highest quality and use this resource to set up the connection.

As for LTE, the quality is determined using the RSRP (although distinguished in NR as 'SS-RSRP'). The ratio between overall channel power and SS-RSRP now depends not only on the overall bandwidth, but also on the numerology used.

3.4 Correction factors

The factors given in the table below allow conversion from (SS-)RSRP to overall channel power. These conversions may be required in coverage prediction, where only the overall eNB[9] or gNB[10] transmit power is known.

One caveat is that, in some NR deployments, the SSB symbols may be boosted by a few dB relative to others to improve acquisition reliability.

Table 3.1: Relationship of RSRP to channel power

Technology	Bandwidth (MHz)	Numerology	RSRP factor (dB)
LTE	5	-	-24.8
	10	-	-27.8
	20	-	-30.8
NR	10	0	-27.6
	20	0	-30.9
	100	0	-38.2
	10	1	-24.6
	20	1	-27.9
	100	1	-35.2

Note that within a numerology, SS-RSRP scales with bandwidth (i.e. 10dB per decade in bandwidth[11]). There is also a 3dB offset between adjacent numerologies.

3.5 Relationship of BW, RSRP and throughput

The relationship between bandwidth and SS-RSRP for an arbitrarily-chosen fixed throughput of 50 Mbit/s is indicated in the table below.

[9] LTE base station
[10] NR base station
[11] The small deviations are due to the impact of guard bands

Table 3.2: Relationship of SS-RSRP to bandwidth for a required throughput of 50 Mbit/s

Numerology	BW (MHz)	SINR	Noise	Sensitivity	SS-RSRP
0	10	9.3	-97.6	-88.3	-115.9
0	100	-6.6	-87.0	-93.6	-131.8
1	10	9.7	-97.8	-87.9	-112.5
1	100	-6.6	-87.1	-93.7	-128.9

These figures are generated using a simplified single-user throughput (SUT) model and described in Section 5.2.1 below. Note that a tenfold increase in bandwidth allows for a corresponding reduction in RSRP of around 16dB in this particular case.

4 5G use cases and performance expectations

If a coverage criterion is to be useful to consumers, it must relate, in some manner, to an expectation of service quality, however defined.

In the process of 5G standardisation and promotion, a very wide range of potential use cases have been defined, each with a specific set of requirements in terms of coverage, reliability, bit rate, latency, etc.

The adaptability and configurability of the 5G standard, together with the fact that applications for 5G are at an early stage of evolution, make it challenging to determine performance thresholds that are both meaningful and comprehensible to non-specialist consumers.

This section provides an overview of 5G network performance metrics and potential use case scenarios and proposes an appropriate baseline performance limit.

4.1 Performance metrics

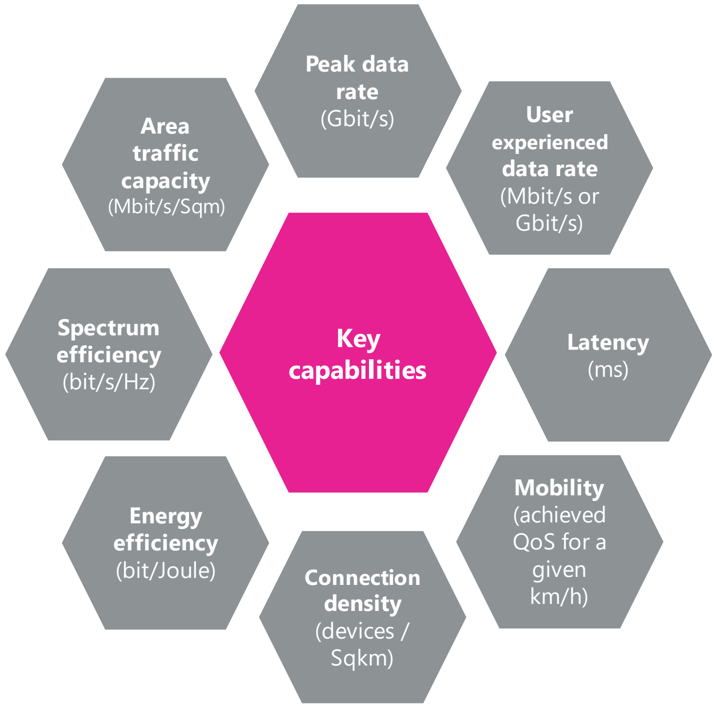
According to ITU-R Recommendation M.2083[12], 5G use cases can be broadly categorised into:

- enhanced Mobile Broadband (eMBB),
- Ultra-reliable and Low Latency Communications (URLLC), and
- massive Machine Type Communications (mMTC).

Eight key ‘capabilities’ (i.e. performance metrics) are described to assess improvements in these usage scenarios.

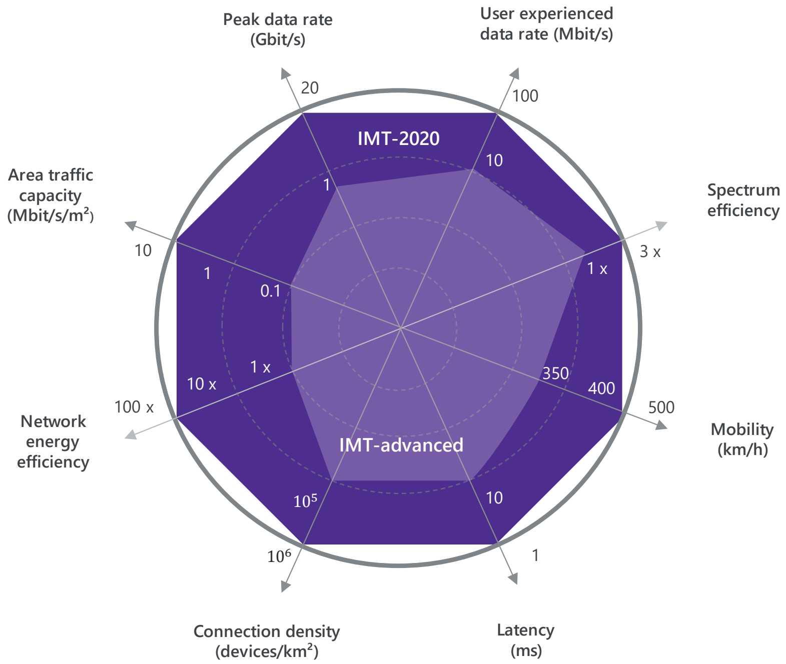
[12] M.2083 : IMT Vision - "Framework and overall objectives of the future development of IMT for 2020 and beyond" (itu.int)

Figure 4.1: 5G capabilities (Source: Plum, based on ITU-R Recommendation M.2083)



The following figure illustrates expected 5G network (i.e. IMT-2020) enhancements in key capabilities with regards to 4.5G networks (i.e. IMT-Advanced).

Figure 4.2: Enhancements in key capabilities (Source: Plum, based on ITU-R Recommendation M.2083)



ITU-R Report 2410[13] expands the number of performance metrics defined in ITU-R Recommendation M.2083 to thirteen. Definitions and requirements associated with these performance metrics are provided in Appendix A.

[13] Minimum requirements related to technical performance for IMT-2020 radio interface(s) (itu.int)

4.2 Potential 5G use cases

There is a considerable amount of published material on potential 5G use cases. The performance metrics discussed above have been used to characterise these use cases. Much of the discussion on potential use cases focuses on 5G service provision across a range of frequency bands and specific sectors, such as transport, media and entertainment, healthcare and manufacturing. We have identified several relevant 3GPP technical specifications which are evolving:

- 3GPP TS 22.261[14] (Service requirements for the 5G system) – provides extensive discussions on basic network capabilities and performance requirements for potential use cases which are categorised into 'high data rates and traffic densities'; 'low latency and high reliability'; 'high accuracy positioning'; 'satellite access'; 'high availability IoT traffic'; and 'high data rate and low latency'.

- 3GPP TS 22.104[15] (Service requirements for cyber-physical control applications in vertical domains) – describes use cases and associated performance requirements for vertical domains including factories of the future, electric power distribution, central power generation and connected hospitals or medical facilities.

- 3GPP TS 22.186[16] (Enhancement of 3GPP support for V2X scenarios) – discusses performance requirements to support V2X scenarios including vehicles platooning, advanced driving, extended sensors and remote driving.

- 3GPP TS 22.263[17] (Service requirements for video, imaging and audio for professional applications) – provides an overview of video, imaging and audio professional applications; and outlines key performance requirements for professional low-latency video and audio transport services; and low latency ultra-reliable imaging/video traffic for medical applications.

- 3GPP TR 38.913[18] (Study on scenarios and requirements for next generation access technologies) – technical report on typical deployment scenarios and associated attributes such as carrier frequency, bandwidth, inter-site distance (ISD), antenna elements, user density and mobility. Deployment scenario categories considered include indoor hotspot, dense urban, rural, urban macro, high-speed, extreme long distance coverage in low density areas, urban coverage for massive connection, highway scenario, urban grid for connected car, commercial air-to-ground, light aircraft and satellite extension.

There are also many other resources related to 5G use cases generated by a range of stakeholders from industry and academia, e.g. GSMA[19], 5G Americas[20, 21], 5G-PPP[22] and UK 5G testbeds and trials[23].

Based on the information available, we have constructed the following table to provide an example set of general use cases and corresponding attributes and performance requirements.

[14] Specification # 22.261 (3gpp.org)
[15] Specification # 22.104 (3gpp.org)
[16] Specification # 22.186 (3gpp.org)
[17] Specification # 22.263 (3gpp.org)
[18] Specification # 38.913 (3gpp.org)
[19] GSMA | Internet of Things
[20] 5G Services & Use Cases - 5G Americas
[21] 5G Spectrum Vision - 5G Americas
[22] White Papers ‹ 5G-PPP (5g-ppp.eu)
[23] Testbeds & trials (uk5g.org)

Figure 4.3: Example use cases and corresponding attributes and performance requirements

Use case	Attributes and performance requirements
Dense urban (Ref: 3GPP TR 38.913 and 3GPP TS 22.261)	**Carrier frequency**: Around 4 GHz (3300 – 4990 MHz) and around 30 GHz (24.25 – 52.6 GHz) **Total bandwidth**: <=200 MHz (UL+DL) 4 GHz and <=1 GHz (UL+DL) 30 GHz **ISD**: 200 m for macro layer and 3 micro sites per macro site **Antenna elements**: Up to 256 BS Tx/Rx ant elements for 4 GHz and 30 GHz; and up to 8 UE Tx/Rx ant elements for 4 GHz and up to 32 UE Tx/Rx ant elements for 30 GHz **Data rate**: 300 Mbit/s (DL); 50 Mbit/s (UL) **User density**: 25,000 /km^2
Urban macro (Ref: 3GPP TR 38.913 and 3GPP TS 22.261)	**Carrier frequency**: Around 2 GHz (1427 – 2690 MHz), around 4 GHz (3300 – 4990 MHz) and around 30 GHz (24.25 – 52.6 GHz) **Total bandwidth**: <=200 MHz (UL+DL) 4 GHz and <=1 GHz (UL+DL) 30 GHz **ISD**: 500 m **Antenna elements**: Up to 256 BS Tx/Rx ant elements for 2 GHz, 4 GHz and 30 GHz; and up to 8 UE Tx/Rx ant elements for 4 GHz and up to 32 UE Tx/Rx ant elements for 30 GHz **Data rate**: 50 Mbit/s (DL); 25 Mbit/s (UL) **User density**: 10,000 /km^2
Rural (Ref: 3GPP TR 38.913 and 3GPP TS 22.261)	**Carrier frequency**: Around 700 MHz (450 – 960 MHz) and around 4 GHz (3300 – 4990 MHz) **Total bandwidth**: <=20 MHz (UL+DL) 700 MHz and <=200 MHz (UL+DL) 4 GHz **ISD**: 1.7 – 5 km **Antenna elements**: Up to 64 BS Tx/Rx ant elements for 700 MHz and up to 256 BS Tx/Rx ant elements for 4 GHz; and up to 4 UE Tx/Rx ant elements for 700 MHz and up to 8 UE Tx/Rx ant elements for 4 GHz **Data rate**: 50 Mbit It/s (DL); 25 Mbit/s (UL) **User density**: 100 /km^2

4.3 Downlink performance requirements

From the summary table above, it can be seen that a downlink target data rate of 50 Mbit/s is identified for both 'urban macro'[24] and 'rural' areas. Given the limited extent of dense urban environments in Ireland, this would seem an appropriate basis for ComReg coverage predictions.

We would also note that the UK regulator, Ofcom, has undertaken a substantial review[25] of throughput rates potentially required for 5G services. This review took, as its basis, the 3GPP Technical Report TR 22.891 "*Feasibility Study on New Services and Markets Technology Enablers; Stage 1*". The results are detailed in Annex 1 of the Ofcom Report, paragraphs A1.17-A1.33. The conclusions, for wide-area services using spectrum below 6 GHz, identify use cases with downlink bitrate requirements of up to 50 Mbit/s (Cloud VR at 1080p, 60fps, Professional 4k 3D mobile video, cloud computer games for connected vehicles), which supports the choice of this data rate for use in prediction.

As noted by Ofcom (Statement of 13 March, 2020[26]) "*Consumer demand for 5G, increased speeds and capacity are likely to grow over time, but beyond these capabilities the long-term picture is very uncertain. It is likely to take some years for demand for 5G services to mature*". Annex 7 of the Ofcom document[27] examines current

[24] i.e. cells providing 'umbrella coverage' to a sunstantial portion of a town, with antennas located above the general rooftop level.
[25] Award of the 700 MHz and 3.6-3.8 GHz spectrum bands: Further consultation on modelling and technical matters (ofcom.org.uk).
[26] Statement: Award of the 700 MHz and 3.6-3.8 GHz spectrum bands (ofcom.org.uk).
[27] Annexes-5-18-supporting-information.pdf (ofcom.org.uk)

expectations and the possible evolution of 5G services, with a particular focus on the spectrum bandwidths likely to be required by operators.

4.4 Consumer perception

Consumer expectations will be conditioned by the current marketing of 5G services, which is representing this as a step change in mobile technology. This implies that whatever coverage thresholds are chosen for 5G should align with a perceptible increase in user quality of experience, with respect to current 4G services.

This is complicated, however, by the reality that the technology differences and data rates experienced on a 700 MHz 5G/NR network are unlikely to be very different from those on an 800 MHz LTE network. The full benefits of 5G will be more apparent at higher frequencies where greater carrier bandwidth can be combined with higher-order MIMO and large arrays of antenna elements.

OpenSignal provide some useful crowdsourced summaries of user experience for networks of different technologies in many countries across the world. The latest data[28] for Ireland (September 2020) shows the "*average download speed experienced by Opensignal users across an operator's networks*" as lying in the range 15.8 – 22.1 Mbit/s.

Bearing in mind that these are average speeds, our suggested value of 50 Mbit/s at the edge of coverage would seem to meet the criterion of representing a perceptible improvement.

4.5 Summary

On the basis of the currently-expected use-cases referred to above, we propose that ComReg's public-facing coverage predictions for 5G be related to a minimum downlink bitrate requirement of 50 Mbit/s.

It will be important to note that use cases and expectations for 5G are currently ill-defined and likely to undergo rapid evolution. There will, therefore, be a need to revisit this assumption in, e.g. 5 years, when patterns of user behaviour are more established, and the hardware/software ecosystem has developed to exploit 5G capabilities.

The proposed bitrate requirement will not be appropriate for millimetre-wave systems (e.g. 26 GHz). Use cases for these frequencies are not well-developed, and anecdotal evidence is that coverage in practice is somewhat binary in nature, with a very sharp transition from high speeds to no availability.

[28] Ireland, September 2020, Mobile Network Experience Report Report | Opensignal

5 Determination of appropriate levels of SS-RSRP

5.1 Accommodation of network differences

In the previous section, we proposed that a download speed of 50 Mbit/s represents a reasonable minimum expectation with which to define the edge of a 5G service area for the next few years.

The coverage predictions available to ComReg will be expressed in terms of SS-RSRP levels, and it is therefore necessary to express the 50Mbit/s criterion in these terms.

As noted in Section 3.5, however, this relationship is a function of many variables, particularly MIMO order and bandwidth. For example, a service provided using 2 x 10 MHz of spectrum, with 2x2 MIMO will require a very different SS-RSRP to deliver 50 Mbit/s than one delivered in 100 MHz of TDD spectrum with 4x4 MIMO.

The same issue applies to LTE services, but as seen in Section 1, only a single RSRP value is used to indicate coverage. This is a sensible, pragmatic approach as the difference in bandwidth used by current operational LTE systems is relatively modest and the added complexity of differentiated thresholds would be unlikely to be justified.

The same cannot be said for 5G services, and it seems clear that it will be necessary to adopt different limits for different bandwidths and frequencies, e.g. 2 x 10 MHz of FDD spectrum and 700 MHz and for 100 MHz of TDD spectrum at 3.5 GHz. The same will be true, to a more dramatic extent, for any future outdoor mobile services delivered at 26 GHz.

The question to be addressed is what 'degree of granularity is required in differentiating between networks'? It will be relatively easy for ComReg to apply different SS-RSRP thresholds to networks using different amounts of bandwidth, but to accommodate differences in MIMO configuration or uplink/downlink ratio in TDD systems (which, in any case, may be dynamic), will be far harder.

It could, therefore, be appropriate to make some simplifying assumptions; such simplifications will, inevitably lead to some distortion of the relative position of operators, either underestimating the coverage of an MNO which has slightly more bandwidth, or a higher-order MIMO scheme than assumed, or the reverse. If chosen appropriately, such differences might be insignificant in comparison to, e.g. variability in handset performance, the details of network traffic and scheduling and propagation model prediction errors.

In our modelling below, we have adopted the following standardised network configurations. Many other options could be chosen with equal validity (e.g. 100 MHz at 3.5 GHz). Note that the frequency is not used in the calculation of SS-RSRP but serves only to indicate the inspiration for the scenario under consideration.

Table 5.1: Modelling scenarios

Scenario	Frequency	Duplex mode	DL:UL	Bandwidth	MIMO order	Numerology
A1	700 MHz	FDD	-	2 x 10 MHz	2	0
A2	800 MHz	FDD	-	2 x 10 MHz	2	0
A3	900 MHz	FDD	-	2 x 10 MHz	2	0
B	1.8 GHz	FDD	-	2 x 25 MHz	4	1
C	2.1 GHz	FDD	-	2 x 15 MHz	4	1

Scenario	Frequency	Duplex mode	DL:UL	Bandwidth	MIMO order	Numerology
D	2.3 GHz	TDD	80:20	30 MHz	4	1
E	2.6 GHz	FDD	-	2 x 30 MHz	4	1
F	3.5 GHz	TDD	80:20	80 MHz	4	1

5.2 Determination of RSRP for given single-user edge throughput

5.2.1 Simplified throughput model

The 3GPP specifications provide a simplified analytic approach for theoretical throughput calculations. This approach is based on the use of an attenuated and truncated form of the Shannon bound to map signal to noise and interference ratio (SNIR) and spectral efficiency (and hence the throughput for a given channel bandwidth). The Shannon bound defines the theoretical maximum spectral efficiency that can be achieved over a communication channel. It is the function of the bandwidth available and SNIR. This approach is included in both LTE and 5G NR specifications[29].

The following function can be used to approximate the spectral efficiency[30] over a channel for a given SNIR assuming perfect link adaptation.

$$Throughput\ (SNIR),\ bps/Hz = \begin{cases} 0 & for\ SNIR \\ \propto \cdot S(SNIR) & for\ SNIR_{MIN} \leq SNIR < SNIR_{MAX} \\ \propto \cdot S(SNIR_{MAX}) & for\ SNIR \geq SNIR_{MAX} \end{cases}$$

where S(SNIR) is the Shannon bound and expressed as S(SNIR) = $\log_2(1+SNIR)$ [bps/Hz]

α is the attenuation factor representing implementation losses

$SNIR_{MIN}$ is the minimum SNIR of the codeset, dB

$SNIR_{MAX}$ is the maximum SNIR of the codeset, dB

The parameters α, $SNIR_{MIN}$ and $SNIR_{MAX}$ can be chosen to represent different modem implementations and link conditions. The following values are proposed for a baseline case (e.g. 1:1 antenna configuration and AWGN channel) in 3GPP 38.921.

α = 0.6 (DL), 0.4 (UL);

$SNIR_{MIN}$ = -10 dB (DL and UL) based on QPSK 1/8 (DL) and 1/5 (UL); and

$SNIR_{MAX}$ = 30 dB (DL) and 22 dB (UL) based on 256 QAM 0.93 (DL) and 64 QAM 0.93 (UL).

In May 2020, Ofcom published a consultation document on the award of 700 MHz and 3.6 – 3.8 GHz spectrum bands[31]. The main theme of the document relates to the use of a 'single throughput user' (SUT) model to

[29] 3GPP TR 36.942 V16.0.0 Annex A and 3GPP TR 38.921 V0.2.0 Section 5.4
[30] Note that 3GPP refer to the bps/Hz metric as 'throughput' rather than the usual 'spectrum efficiency'.
[31] Award of the 700 MHz and 3.6-3.8 GHz spectrum bands: Further consultation on modelling and technical matters (ofcom.org.uk)

support Ofcom's view that MNOs could provide a wide range of 5G services with channel bandwidths smaller than 80 MHz in 3.6 – 3.8 GHz. In the consultation document, SNIR vs. SUT plots are derived for a range of 5G NR configurations by applying a set of adjustments to the mapping function described above. These adjustments are made to accommodate the implications of MIMO; higher order modulations; carrier aggregation; and TDD uplink and downlink ratio.

The consultation document presents the following modified throughput estimation function, which combines the mapping function and the 5G NR throughput calculation formula provided in Section 4.1.2 of 3GPP TS 38.306[32].

$$SUT\_Throughput, (bps) = \begin{cases} 0 \; for \; SINR < SINR_{min} \\ \left[TBW * \alpha * S(SINR) * F_{TDD} * v_{Layers} * (1 - CA) \right] \; for \; SINR_{min} < SINR < SINR_{max} \\ SUT\_Thr_{max} \; for \; SINR > SINR_{max} \end{cases}$$

where TBW is the total aggregate transmission bandwidth;

S(SNIR) is the Shannon bound for a single spatial layer, S(SNIR) = $\log_2$(1+SNIR) [bps/Hz];

α is the attenuation factor representing implementation losses, 0.6 (DL) and 0.55 (UL);

$SNIR_{MIN}$ is the minimum SNIR of the codeset, -10 dB (DL and UL);

SUT_Thr_{max} is the maximum throughput of the codeset (bps) calculated using the formula provided in Section 4.1.2 of 3GPP TS 38.306[33];

$SNIR_{MAX}$ is the maximum SNIR at which SUT_Thr_{max} is reached;

F_{TDD} is the TDD factor, e.g. 0.75 in the downlink and 0.25 for the uplink for 3:1 frame structure or 0.5 in the downlink and uplink for 1:1 frame structure;

ν_{Layers} is the number of SU-MIMO spatially multiplexed data layers which depends on the scenario, (e.g. four in the downlink and two in the uplink); and

CA is the additional signalling overhead for carrier aggregation. This value is 0 for single carrier scenarios and 0.06 for scenarios with two carriers.

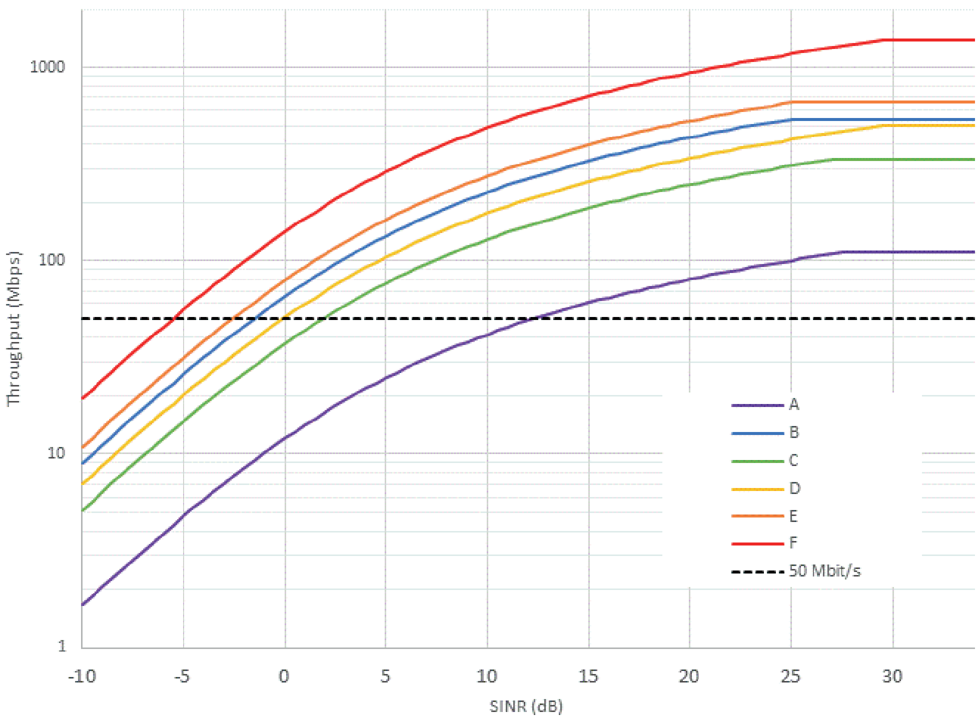
Plum have implemented this simple model to derive required SINR values for the baseline 50 Mbit/s throughput under different network assumptions.

5.2.2 SINR calculations

The SUT model has been applied to the scenarios described in Table 5.1, and the resulting throughput curves are shown below.

[32] Specification # 38.306 (3gpp.org)
[33] This ensures that the throughput curves are truncated appropriately when considering that 5G NR supports up to 256QAM 9/10 (DL) and 64QAM 9/10 (UL).

Figure 5.1: NR: Single-user throughput vs SINR



The relevant SINR values are tabulated below.

Table 5.2: SINR values

Scenario	SINR (50 Mbit/s)
A	12.3 dB
B	-1.5 dB
C	1.9 dB
D	-0.1 dB
E	-2.6 dB
F	-5.5 dB

5.2.3 SINR to SS-RSRP

Transformation of the SINR to an SS-RSRP value requires an assumption to be made regarding receiver noise. We assume[34] a UE noise figure of 7dB in the calculations below.

[34] See, e.g. Holma, H. et al, "5G Technology: 3GPP New Radio", John Wiley & Sons, 2020

An allowance should also be made for the required cell-edge probability of service. We have assumed[35] a location variability of 8dB, giving a shadowing margin of 10.3dB at 90% probability. In more detailed predictions, a frequency-dependent value of location variability might be justified.

Table 5.3: RSRP values

Scenario	SINR (50 Mbit/s)	Receiver noise	Sensitivity	Scaling factor	SS-RSRP (median)	SS-RSRP (90%)
A	12.3 dB	-97.8 dBm	-85.5 dBm	-27.6 dB	-113.1 dBm	-102.8 dBm
B	-1.5 dB	-93.3 dBm	-94.8 dBm	-28.9 dB	-123.7 dBm	-113.4 dBm
C	1.9 dB	-95.7 dBm	-93.8 dBm	-26.5 dB	-120.3 dBm	-110.0 dBm
D	-0.1 dB	-92.5 dBm	-92.6 dBm	-29.7 dB	-122.3 dBm	-112.0 dBm
E	-2.6 dB	-92.5 dBm	-95.1 dBm	-29.7 dB	-124.8 dBm	-114.5 dBm
F	-5.5 dB	-88.0 dBm	-93.5 dBm	-34.2 dB	-127.7 dBm	-117.4 dBm

The values in the right-hand column represent the minimum usable service limit for a 5G service of 50 Mbit/s downlink in each scenario.

Given the uncertainty in 5G use cases (and therefore in appropriate thresholds) as well as the likely variations in bandwidth and configuration between different operators, it seems inappropriate to apply a high level of granularity to the RSRP thresholds. We therefore propose simplifying the thresholds by taking average values[36] of RSRP for some pairs of scenarios, as indicated below.

Table 5.4: RSRP values

Band(s)	Scenarios	SS-RSRP (90%)
< 1 GHz	A	-102.8 dBm
1.8 & 2.1 GHz	B, C	-111.7 dBm
2.3 & 2.6 GHz	D, E	-113.3 dBm
3.5 GHz	F	-117.4 dBm

The BEREC Common Position on '*Technical specifications for providing relevant and comparable information on mobile coverage to European consumers*' as set out in Document (18) 237[37] encourages NRAs to "*to provide consumers with a multi-level coverage information*". Examples are given where these levels are defined in terms of service availability (e.g. 95%, 75%, 50% or none) or of different margins of field strength (e.g. field strength intervals of 10dB).

It would, in principle, be possible to relate such contours to various levels of service availability (e.g. an additional margin of 3dB would take availability from 90% to 95%) or to maximum throughput (e.g. an additional 10dB margin would increase bitrate by a certain amount).

[35] See, e.g. ITU-R Recommendation P.1546
[36] In dB terms
[37] BEREC Common Position on information to consumers on mobile coverage (europa.eu)

Both are problematic, however, as practical interpretation of probabilities by users is notoriously difficult and the throughput uplift will vary depending on the starting point on the truncated Shannon curve.

We propose, therefore, to align the display of 5G contours with the approach used for other technologies and apply contours at 10dB intervals.

6 Recommendations for 5G outdoor coverage thresholds

We recommend that ComReg should use a set of coverage thresholds for 5G services that take account, to some degree, of the different bandwidth and technical configurations used in each band.

Because 5G use-cases are presently rather ill-defined or speculative, we feel that it would be inappropriate to imply that any thresholds correspond to precise quality of service definitions.. While it would, in principle, be possible to tailor limits on a carrier-by-carrier basis and to accommodate a wide range of NR configuration parameters, there is the risk that such limits would need regular updating and give a spurious impression of accuracy.

While it is probably desirable (and may be required) that the derivation of the thresholds be in the public domain, it is probably not helpful to consumers to attempt to link contours explicitly with technical criteria. A form of words such as "*the contours in these maps are intended to give an intuitive indication of 5G coverage*" would therefore seem appropriate.

Table 6.1: Recommended 5G coverage thresholds

SS-RSRP (dBm) Coverage Threshold	Description	< 1 GHz	1.8 GHz & 2.1 GHz	2.3 GHz & 2.6 GHz	3.5 GHz
Very good	Strong signal strength with maximum data speeds	≥ -82.8	≥ -91.7	≥ -93.3	≥ -97.4
Good	Strong signal strength with good data speeds	≥ -92.8	≥ -101.7	≥ -103.3	≥ -107.4
Fair	Fast and reliable data speeds may be attained but marginal data speeds with data dropouts are possible at weaker signal levels.	≥ -102.8	≥ -111.7	≥ -113.3	≥ -117.4
Fringe	Marginal or poor data speeds with data disconnections likely to occur	≥ -112.8	≥ -121.7	≥ -123.3	≥ -127.4

SS-RSRP (dBm) Coverage Threshold	Description	< 1 GHz	1.8 GHz & 2.1 GHz	2.3 GHz & 2.6 GHz	3.5 GHz
No coverage	Signal strength in which no coverage is available to consumers	< -112.8	< -121.7	< -123.3	< -127.4

Plum recommend the display of outdoor mobile coverage mapping data for 5G services on a technology basis, rather than display per individual 5G spectrum band. This approach will replicate the existing display format for 2G,3G,4G and also simplify the experience for consumers who want to understand the levels of outdoor mobile 5G coverage across Ireland.

We propose, therefore, that ComReg implement a logical, geographically - based outdoor coverage comparison (SS-RSRP) of the individual 5G spectrum bands represented in table 6.1. This approach will enable the accurate definition of 5G coverage thresholds on a single technology basis.

We are not currently recommending any limits for use with 5G services in FR2 (millimetre waves). Not only are use cases insufficiently well understood, but it seems unlikely that, due to issues of scale, traditional coverage plots would have great utility to consumers.

It should also be noted that at present, with the non stand-alone (NSA) implementation, 5G coverage is only possible where a 4G/LTE service also exists.

Appendix A Technical performance requirements

ITU-R Report 2410 describes the following key capabilities for 5G networks.

Figure A.1: Technical performance requirements

Performance metric	Definition	Requirement
Peak data rate	The maximum achievable data rate under ideal conditions (bit/s) for a single mobile station.	The minimum requirements are 10 Gbit/s for the uplink and 20 Gbit/s for the downlink for the eMBB usage scenario.
Peak spectral efficiency	The maximum data rate under ideal conditions normalised by channel bandwidth in bit/s/Hz.	The minimum requirements are 15 bit/s/Hz for the uplink and 30 bit/s/Hz for the downlink for the eMBB usage scenario.
User experienced data rate	The data rate (Mbit/s) at the 5% point of the cumulative distribution function (CDF) of the user throughput.	For dense urban eMBB test environment, the target values are 50 Mbit/s for the uplink and 100 Mbit/s for the downlink.
5th percentile user spectral efficiency	The 5% point of the CDF of the normalized user throughput (bits/s/Hz).	Defined for eMBB test scenarios including • indoor hotspot (0.21 bits/s/Hz for the uplink and 0.3 bits/s/Hz for the downlink), • dense urban (0.15 bits/s/Hz for the uplink and 0.225 bits/s/Hz for the downlink), and • rural (0.045 bits/s/Hz for the uplink and 0.12 bits/s/Hz for the downlink).
Average spectral efficiency	The aggregate throughput of all users divided by the channel bandwidth and the number of Transmission Reception Points (TRxPs)[38] in bits/s/Hz/TRxP.	Defined for eMBB test scenarios including • indoor hotspot (6.75 bits/s/Hz/TRxP for the uplink and 9 bits/s/Hz/TRxP for the downlink), • dense urban (5.4 bits/s/Hz/TRxP for the uplink and 7.8 bits/s/Hz/TRxP for the downlink), and • rural (1.6 bits/s/Hz/TRxP for the uplink and 3.3 bits/s/Hz/TRxP for the downlink).
Area traffic capacity	The total traffic throughput served per geographic area in Mbit/s/m^2.	The target value for the downlink is 10 Mbit/s/m^2 defined for indoor hotspot eMBB test environment.
User plane latency	The contribution of the radio network to the time from when the source sends a packet to when the destination receives it in ms.	The minimum requirements are 4 ms for eMBB and 1 ms for URLLC usage scenarios.
Control plane latency	The transition time from a most battery efficient state (e.g. idle state) to the start of continuous data transfer (e.g. active state) in ms.	The minimum requirement is 20 ms defined for eMBB and URLLC usage scenarios. A lower control plane latency figure of 10 ms is encouraged.

[38] Antenna array with one or more antenna elements available to the network located at a specific geographical location for a specific area

Performance metric	Definition	Requirement
Connection density	The total number of devices fulfilling a specific quality of service (QoS) per unit area (per km^2).	The minimum requirement is 1,000,000 devices per km^2 defined for the evaluation of mMTC usage scenarios.
Energy efficiency	The capability of minimising the radio access network energy consumption in relation to the traffic capacity provided, defined for the evaluation of eMBB usage scenarios.	A support for high sleep ratio[39] and long sleep duration[40] is required.
Reliability	The capability of transmitting a given amount of traffic within a predetermined time duration with high success probability, defined for the evaluation of URLLC usage scenarios.	The minimum requirement for the reliability is $1\text{-}10^{-5}$ success probability[41].
Mobility	The maximum mobile station speed at which a defined QoS (expressed in terms of normalised traffic channel data rates for the uplink) can be achieved in km/h.	Defined for eMBB test scenarios including • indoor hotspot (1.5 bits/s/Hz for 10 km/h), • dense urban (1.12 bits/s/Hz for 30 km/h), and • rural (0.8 bits/s/Hz for 120 km/h and 0.45 bits/s/Hz for 500 km/h).
Mobility interruption time	The shortest time duration supported by the system during which a user terminal cannot exchange user plane packets with any base station during transitions in ms.	Defined for eMBB and URLLC usage scenarios and the minimum requirement is 0 ms.
Bandwidth	The maximum aggregated system bandwidth.	The minimum requirement is 100 MHz.

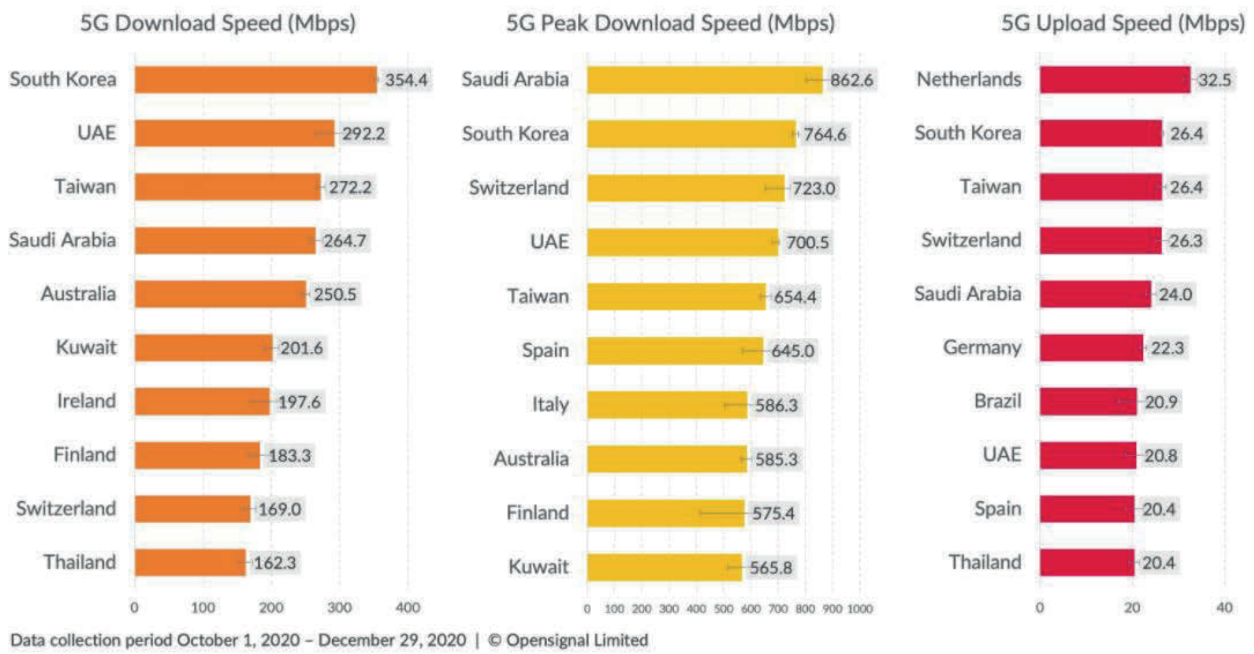
[39] The sleep ratio is the fraction of unoccupied time resources (for the network) or sleeping time (for the device) in a period of time corresponding to the cycle of the control signalling (for the network) or the cycle of discontinuous reception (for the device) when no user data transfer takes place.
[40] The sleep duration is the continuous period of time with no transmission (for network and device) and reception (for the device).
[41] Associated with transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1 ms in channel quality of coverage edge for the Urban Macro-URLLC test environment, assuming small application data (e.g. 20 bytes application data + protocol overhead).

Appendix B Example limits quoted for 5G coverage

As noted in Section 2, BEREC have concluded that it is premature to seek to provide harmonised limits for 5G coverage. We have also found no evidence of any limits defined or referred to by regulators.

We have noted that Opensignal provides '5G user experience' data for a number of countries where 5G networks are deployed[42]. The following figure compares top ten countries in terms of 5G average download and upload speeds as well as peak download speed (i.e. the average speed experienced by the top 2% of users). These results are based on the real-world 5G speeds where users had an active 5G connection, mostly on non-standalone access networks.

Figure B.1: Top ten 5G speeds (Source: Opensignal) (NB: check OpenSignal copyright before finalising)



We have also examined evidence from a number of administrations/operators.

B.1 France

The ANFR website directs users to the websites of individual MNOs for information on 5G coverage. All MNOs publish coverage maps, showing a single contour for 5G coverage. The quality of service associated with the contour varies, however, according to the band. Thus:

SFR: Theoretical maximum downlink bitrate 2Gb/s (3.5 GHz) or 995 Mb/s (2.1 GHz)

Orange: Theoretical maximum downlink bitrate 2.1Gb/s (3.5 GHz) or 615 Mb/s (2.1 GHz)

[42] Market Insights | Opensignal

B.2 South Korea

According to the mobile operator KT's coverage maps[43], the highest speed (3.5 GHz) is 1.5 Gbps while highest speed on 5G+LTE connections is 2.5 Gbps.

B.3 USA

T-Mobile's coverage maps present a number of coverage levels: limited, fair, good, excellent signal strengths for its 5G network[44]. However, there is no information on the signal strength or data rates associated with these levels.

Similarly, AT&T and Verizon coverage maps only inform whether there is a 5G coverage at a given location with no further information on the threshold signal level or data rate[45,46]. Information on AT&T performance characteristics[47] indicate that the typical download data range is 46.2 – 140.4 Mbps while the typical upload data range is 6.6 – 23.1 Mbps. Latency figures are in the range 25 – 41 ms.

B.4 Canada

Telus's mobile coverage maps state that '*Manufacturer's rated peak download speeds: 5G, up to 1700 Mbps*'[48]. Bell's 5G network data indicates a theoretical peak download speed of up to 1.7 Gbps in major cities across Canada with average expected speeds between 69 – 385 Mbps in the Greater Toronto Area[49]. Rogers's coverage maps do not provide signal strength or data rate information[50].

B.5 Australia

Telstra provides a coverage map showing where 5G services are available with no details on signal strength or data rate[51]. Optus coverage maps provide three levels of signal quality with no associated signal strength or data rate information[52]. It is however stated that the average download speed in their 5G network is 239 Mbps and also implied that the minimum target download speed is 50 Mbps[53]. Vodafone Australia provides a list of suburbs where 5G service is available with no further coverage data[54].

B.6 Switzerland

[43] [고객지원] 서비스 커버리지|글로벌 No.1 KT
[44] 5G & 4G LTE Coverage Map: Check Your Cell Phone Service | T-Mobile (t-mobile.com)
[45] 5G Coverage Map - AT&T
[46] Verizon Coverage Map: Nationwide 5G and 4G LTE Network Cell Phone Coverage | Verizon
[47] Performance Characteristics | AT&T Broadband
[48] 5G and 4G LTE, HSPA+ & LPWA network coverage map | TELUS
[49] 5G Network | Bell Business Mobility
[50] Network Coverage Map | Rogers
[51] Our Coverage & Rollout Maps - Telstra
[52] Mobile Network Coverage (optus.com.au)
[53] 5G - Optus
[54] The Vodafone 5G Network | Vodafone Australia

Swisscom, Salt mobile and Sunrise mobile provide 5G coverage maps with no signal strength or data rate details[55,56,57]. The Sunrise mobile coverage map has five service level indicators.

B.7 UK

The EE 5G coverage map has five service level indicators but no signal level or data rate are provided[58]. The O2 coverage map does not distinguish between mobile technologies[59]. The Vodafone UK coverage map displays good, limited or no outdoor coverage level. The associated range of 5G data rates is very broad: 0.4 - 850 Mbps (DL) and 0.125 - 50 Mbps (UL)[60].

55 Mobilfunk-Abdeckung (begasoft.ch)
56 Coverage | Salt.
57 5G with Sunrise - the new network generation in Switzerland
58 Coverage and network status checker (ee.co.uk)
59 O2 Network Coverage Checker | 2G, 3G, 4G and 5G Coverage
60 Network Status checker | Check your signal (vodafone.co.uk)