Low-band spectrum for 5G

The need for sub-1 GHz spectrum to deliver the vision of 5G

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1 Executive summary

To realise the visions of IMT-2020 (5G)[1], spectrum is required in low- (sub-1 GHz), mid- (1–7 GHz) and high-bands (mmWaves). While low-band (sub-1 GHz) spectrum for mobile has always been relatively scarce, the transition to 5G, the scarcity of low-band (sub-1 GHz) spectrum is becoming extremely problematic. This report examines why governments and regulators must take a fresh look at the need for additional sub-1 GHz spectrum to deliver 5G to urban and rural areas.

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Exhibit 1: The benefits of additional sub-1 GHz spectrum for IMT

Reduce the cost of extending coverage to rural populations by 33%	Deliver a good user experienced data rate for 5G-connected vehicles on rural roads	Improve digital equality with a good 5G user-experienced speed in rural areas

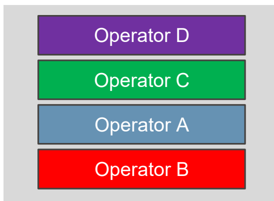


Provide sufficient capacity for 5G Fixed Wireless Access tor isolated rural buildings	Enable smart agriculture, notably precision farming	30-50% improvement in indoor speeds in cities, small towns and villages



Consistent outdoor speed coverage in narrow alleys and other hard-to-reach places	Cost-efficient 5G capacity solution for areas where mid-bands do not reach	Opportunity for efficient sub-1 GHz band reorganisation using wide channels





Source: Coleago

[1] Recommendation ITU-R M.2083-0 (09/2015), "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond"
[2] Report ITU-R M.2441-0 (11/2018), "Emerging usage of the terrestrial component of International Mobile Telecommunication (IMT)" and Report ITU-R M.2410, "Minimum requirements related to technical performance for IMT-2020 radio interface(s)"

Rural 5G

Coleago's study found that an additional 2x20 MHz could reduce an operator's cost of building rural 5G coverage to unconnected areas by 33%.

As of 2020, 43.8% of the world's population lives in rural areas[3]. Many governments have rural mobile broadband coverage objectives to extend mobile operators' 4G and 5G footprints and close the urban-rural digital divide. Because rural areas are much larger than urban areas, the cost of building cell sites to cover them is higher. At a given 5G speed target, there is a direct relationship between the amount of sub-1 GHz spectrum available to mobile operators and the number of cell sites required to cover a specific area.

Coleago's study found that an additional 2x20 MHz can reduce an operator's cost of building rural 5G coverage to unconnected areas by 33%.

Agricultural areas – rural areas where people live and work – make up around 33% of the world's landmass (cities account for around 2%) and covering all agricultural areas will be challenging. Until now, policymakers have focussed primarily on population and transport link coverage targets for mobile broadband. However, agricultural IoT using 5G, for example for precision farming would requires area coverage and not only population coverage, in those areas where it is economically viable to do so. This means that making additional sub-1 GHz spectrum available for mobile in order to bring down the cost of providing rural area coverage is becoming more important if countries want to enable the digital transformation of agriculture.

Cost-efficient capacity solutions for rural 5G

The more sub-1 GHz is made available, the lower the cost per MHz deployed.

The more sub-1 GHz spectrum is made available, the lower the cost per MHz deployed. 5G in sub-1 GHz can be deployed in a wider channel than 4G and, if additional spectrum is made available, multiple competing operators could each deploy in a downlink channel bandwidth up to 35 MHz. This could reduce the cost per MHz deployed by 62%, which is significant for making broadband speed coverage in rural more affordable.

Two or three bands can be combined in a single sub-1 GHz radio and antenna. For example, the total cost of ownership for a dual-band radio and antenna is only 50% higher than a single-band radio and antenna.

Consistent 5G speed coverage in built-up areas

It is often assumed that sub-1 GHz spectrum is only needed for rural coverage, but cities need it, too. Apart from coverage, user-experienced speed is key. Not only must 5G deliver a near-guaranteed speed of 100 Mbit/s in the downlink (DL) and 50 Mbit/s in the uplink (UL) city-wide, but reliability is also important, considering Ultra-reliable and Low-latency communications (URLLC) are one of the pillars for 5G use cases

Since inter-site distances in cities are relatively short, coverage and capacity are provided by mid-bands. Even with this dense cell structure, around 15% of traffic is still carried by low-bands because mid-band coverage is not ubiquitous. Large areas of cities are covered by buildings and there are many hard-to-reach places in built-up areas, such as narrow alleys, city courtyards and curved narrow streets in urban areas, small towns and villages. Although these "not-spots" represent a small area overall, they have a substantial impact on the 5G user experience because they are where people live and work.

If an additional sub-1 GHz spectrum was made available for mobile, this could increase indoor speeds by 30 to 50%.

While the number of indoor 5G sites is growing, the building penetration of sub-1 GHz spectrum is essential for delivering consistent 5G speed coverage in built-up areas. The quantum of sub-1 GHz spectrum also matters as there is a direct relationship between the amount of spectrum and user-experienced DL and UL speeds. If an additional 2x35 MHz or 2x40 MHz of sub-1 GHz spectrum is made available for mobile, depending on the region and country this could increase indoor speeds by 30 to 50%.

[3] World Bank staff estimates based on the United Nations Population Division's World Urbanization Prospects: 2018 Revision.

The sub-1 GHz spectrum capacity gap

Much of the focus on making spectrum available for 5G has been on mid- and high-bands (mmWaves). Sub-1 GHz spectrum accounts for around 17% of spectrum and mid-bands for 83%. However, since higher orders of Multiple Input Multiple Output (MIMO) can be deployed in mid-bands, the share of sub-1 GHz area traffic capacity is only 7%. However, sub-1 GHz bands carry 10-20% of traffic in urban areas, which means there is a wide gap between sub-1 GHz area traffic capacity and area traffic demand.

Sub-1 GHz spectrum for legacy technology

Additional sub-1 GHz would enable mobile operators to build sufficient capacity for 5G while serving legacy users and uses.

Due to the need to serve customers without VoLTE-enabled phones, as well as legacy M2M applications, mobile operators typically need to maintain either a 2G or 3G coverage layer using 2x20 MHz. Additional sub-1 GHz would enable mobile operators to build sufficient sub-1 GHz capacity for 5G while also serving legacy users and uses.

The opportunity for sub-1 GHz band reorganisation

In most markets, mobile operators hold small amounts of spectrum in each of the sub-1 GHz bands assigned. It may be possible to defragment sub-1 GHz holdings in a long-term time-frame. So, instead of holding smaller amounts of spectrum in three sub-1 GHz bands, operators could hold a larger amount of spectrum (a wider channel) in a single band. An expanded band arrangement would increase spectral and investment efficiency.

Additional sub-1 GHz spectrum versus carrier aggregation

Carrier aggregation is not a substitute for making additional sub-1 GHz spectrum available.

Carrier aggregation (CA) of sub-1 GHz bands does not increase total capacity nor does it improve coverage. It is therefore not a substitute for making additional sub-1 GHz spectrum available and is not currently feasible in user devices. Furthermore, CA of two 10 MHz channels versus one 20 MHz channel carries a usable bandwidth penalty of 5.7% and nearly doubles signalling overhead. Given the scarcity of sub-1 GHz spectrum, good practice in spectrum management would be to allocate wider bands to operators rather than splitting all bands between operators. Additional sub-1 GHz spectrum would make this possible.

Options for additional sub-1 GHz spectrum for IMT

Terrestrial broadcast TV is declining as viewers switch to other forms of distribution and broadcasters seek to avoid the cost of operating a high-power high-tower broadcast network.

Additional sub-1 GHz spectrum can be found in the range below the 700 MHz bands and in North America below the 600 MHz band. Depending on the country, the frequency range is used for broadcast. However, the use of high-tower high-power transmitters for broadcast TV is declining. Broadcast content and distribution are fundamentally separate issues, as TV channels care how they can reach the widest audience at the lowest cost with the best media product. Demand and technology trends favour a shift away from dedicated terrestrial TV to alternative forms of delivery.

This has significant benefits, including:

- A better audio-visual experience for viewers with a converged linear, on-demand and interactive offer;
- Avoiding the cost of operating a high-tower and high-power broadcast infrastructure; and
- Making additional sub-1 GHz spectrum available for 5G, which improves the user experience, helps to overcome the urban-rural digital divide and reduces the cost per bit..

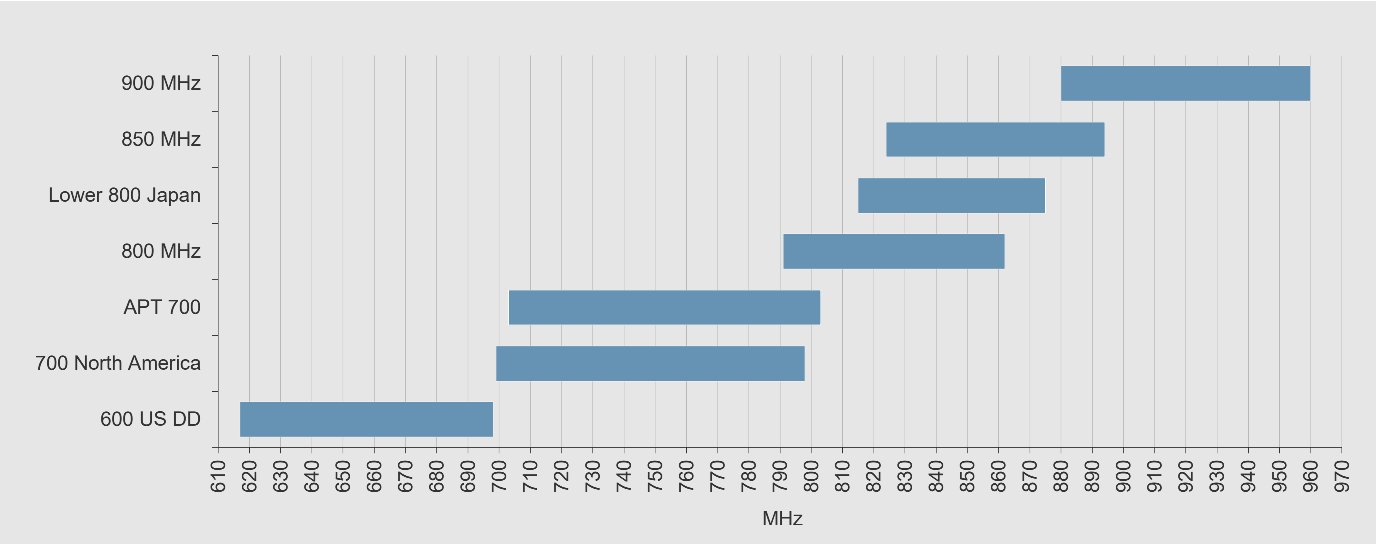
Licence fees for additional sub-1 GHz spectrum

Governments often assume that additional sub-1 GHz is of significant value to mobile operators because it reduces the number of sites to be built. However, the value, in fact, accrues to consumers and reduces the cost of coverage subsidies and the service. High spectrum prices lead to limited investment capabilities and, therefore, coverage, quality and final prices to consumers are impacted.

2 Sub-1 GHz bands for IMT

Depending on the region, as of January 2021, there were three main sub-1 GHz band categories specified by 3GPP for 4G and 5G in the 617–960 MHz range as shown in Exhibit 2. Depending on the region and country, between 180 and 210 MHz of sub-1 GHz spectrum have been identified for IMT. In some countries, not all the spectrum has been assigned, particularly for the APT 700 band. For some bands, such as the APT 700 supplementary DL band n67 (20 MHz), there is not yet an ecosystem. A list of 3GPP-specified sub-1 GHz bands can be found in Appendix A.

Exhibit 2: 3GPP Sub-1 GHz bands



Source: 3GPP, Coleago.

The use of different bands roughly follows the ITU regions, but there are differences between countries:

- 900 MHz (Band 8, 2x35 MHz) is the original GSM band and deployed in Regions 1, 2 (Latin America) and 3. In Regions 2 and 3, some countries mixed 900 MHz (Band 8) and 850 MHz (Band 5) assignments, but in terms of total sub-1 GHz availability this does not make much of a difference.
- 850 MHz (Band 5, 2x25 MHz) is the first cellular band for North America and is also used in other Region 2 countries and in Region 3.
- 800 MHz (Band 20, 2x30 MHz) is the EU Digital Dividend band used as the first LTE (4G) coverage band in Region 1.
- APT 700 (Band 28, 2x45 MHz) is the LTE (4G) coverage band for Asia Pacific and it has also been adopted in Latin America. However, in Region 1 where the band is used as the 5G coverage band, only 2x30 MHz is available. There is also 20 MHz of supplementary DL spectrum (Band 67) specified in the Band 28 centre gap, but it has only been assigned in a few countries.
- 700 MHz North America consists of a total of 80 MHz, including 10 MHz of supplementary downlink (SDL) spectrum.
- 600 MHz US DD (Band n71, 2x35 MHz) has been assigned and is used in the US and Canada. It is in the 5G coverage band.

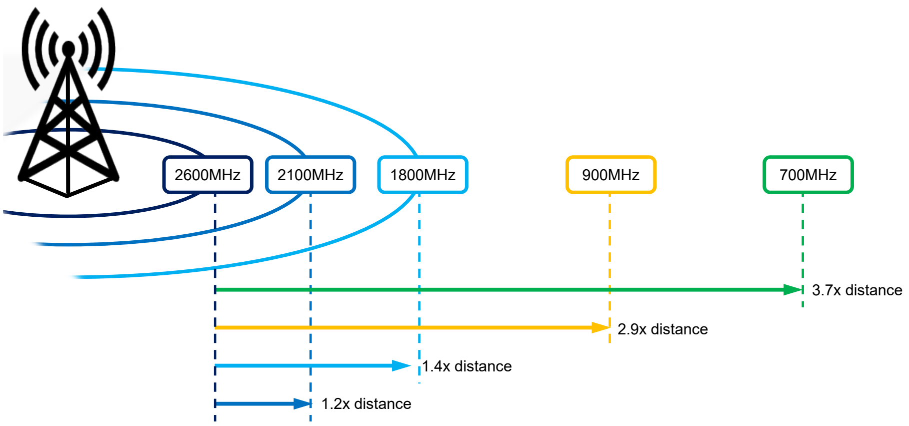
3 Advantages of sub-1 GHz spectrum

Lower frequencies have superior propagation characteristics, which determines how far the signal can travel and how well it can penetrate buildings.

Lower frequencies have superior propagation characteristics, which determines how far a signal can travel and how well it can penetrate buildings. For example, using 700 MHz instead of 1800 MHz produces a path loss gain of 13.4 dB thus creating better indoor coverage and wide-area coverage. The higher the path loss gain, the wider the coverage range and the better the in-building penetration. Sub-1 GHz spectrum is therefore essential in both rural and urban environments:

- In rural areas, the cell range advantage makes it possible for operators to cover wide areas cost-effectively. For example, in open space 700 MHz reaches 2.6 times further than 1800 MHz. To provide equivalent geographic 5G speed coverage with 1800 MHz spectrum as 700 MHz spectrum, around three to four times the number of cell sites would be required.[4] This takes into account differences in path loss and the fact that there is more 1800 MHz spectrum available than 700 MHz, which affects cell edge speed.
- In built-up areas, including cities, small towns and villages, sub-1 GHz spectrum is essential to provide in-building coverage where mid-band spectrum cannot penetrate sufficiently.

Exhibit 3: Coverage comparison in free space depending on frequency



Source: Coleago.

However, sub-1 GHz spectrum has limitations compared to mid-band spectrum, including inherent lack of bandwidth and lower MIMO capabilities. Due to the longer wavelength, sub-1 GHz antennas are much larger than mid-band antennas. This limits the opportunity to increase spectral efficiency using MIMO and beam-forming antennas. For example, in the 3500 MHz band, 64T64R can be deployed whereas, in the sub-1 GHz band, 4T4R is the maximum achievable. This widens the capacity gap between sub-1 GHz spectrum and mid-bands even more.

4 The sub-1 GHz spectrum capacity gap

Excluding mmWave, sub-1 GHz spectrum typically accounts for 17% of spectrum and mid-bands for 83%, depending on the country (see Exhibit 4). This calculation includes spectrum that is on spectrum assignment roadmaps, but not yet assigned to mobile operators.

However, as mentioned above, the larger antennas required for sub-1 GHz spectrum limit the opportunity to increase spectral efficiency using MIMO and beam forming. This

[4] Theoretically, over four times the number of sites are needed to cover the same area with 1800 MHz. However, the real-world figure is lower. The precise figure depends on local propagation conditions, the amount of spectrum available in 700 MHz versus 1800 MHz, MIMO configurations in each band and the distribution of demand over the area covered by a site.

matters both in urban areas where traffic density (Gbit/s/km^2) is higher and in rural areas where there are both low traffic density and low site density.

The urban capacity gap

In cities, mobile network dimensioning is driven by the need to provide capacity and the inter-site distances are small relative to rural areas. Mid-bands can and need to be deployed at a much higher density, which gives mid-bands additional capacity advantage.

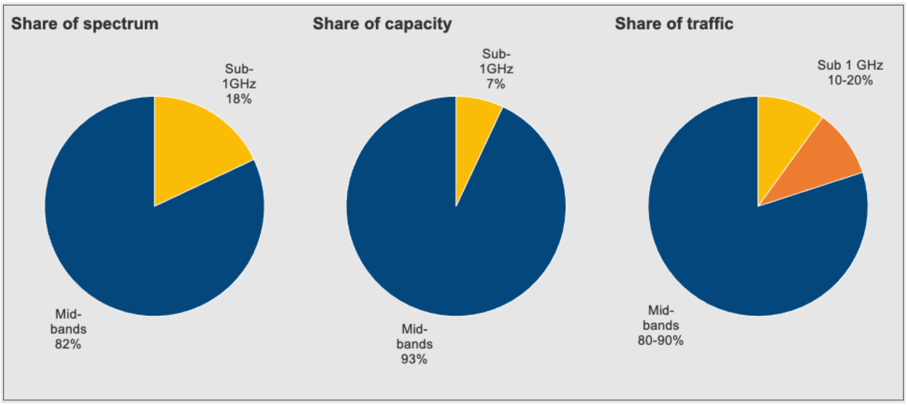
While the share of sub-1 GHz spectrum is typically 18%, due to the ability to deploy higher orders of MIMO in mid-bands, the share of capacity is only 7%. Yet, sub-1 GHz bands typically carry 10-20% of traffic in urban areas.

Exhibit 4 shows the sub-1 GHz share of spectrum as a percentage of total sub-1 GHz and mid-band spectrum (excluding mmWaves), the share of capacity provided by sub-1 GHz spectrum and the share of traffic carried by sub-1 GHz spectrum. With some variation between regions and countries, the share of sub-1 GHz spectrum is typically 18%. However, due to the ability to deploy higher orders of MIMO in mid-bands, the share of capacity is only 7%.

Despite this, sub-1 GHz bands typically carry 10-20% of traffic[5], even in urban areas,. This means there is a wide gap between sub-1 GHz area traffic capacity and area traffic demand.

If more mid-band spectrum is made available in the future (for example, via 3.3–4.2 GHz, 4.8 GHz and 6 GHz), the capacity gap between sub-1 GHz spectrum and mid-bands widens. Further network densification in cities by means of small cells is likely to reduce the traffic that can only be carried on sub-1 GHz bands but given the projected growth in mobile data traffic density, sub-1 GHz bands will face severe congestion compared to mid- and high-band capacity unless additional low-band spectrum is made available.

Exhibit 4: Sub-1 GHz share of spectrum, capacity and traffic



Source: Coleago. See appendix for detailed calculation.

The rural capacity gap

Rural areas are characterised by low population density and relatively low traffic density. The main driver of network costs is the need to build coverage. The larger the inter-site distances, the lower the cost of coverage, which is key to ensure an economically feasible rural 5G deployment.

Exhibit 3 shows the coverage range advantage of sub-1 GHz spectrum compared to mid-bands. Due to larger inter-site distances in rural areas, rural broadband access relies heavily on sub-1 GHz spectrum.

Unless additional sub-1 GHz spectrum is made available for IMT, the urban-rural digital divide may widen rather than narrow.

Therefore, unless additional sub-1 GHz spectrum is made available for IMT, the urban-rural digital divide may widen rather than narrow.

[5] Based on data gathered from mobile operators during Q1 2022

5 Broadband connectivity in the context of land use and population

Section 4 covered why sub-1 GHz spectrum has an advantage over other frequencies in terms of wide area coverage and in-building penetration. The value of sub-1 GHz spectrum for global 5G connectivity therefore depends on land use and topology.

Around 1 to 3%[6] of global land area is built-up areas covered by settlements and infrastructure. This includes cities and rural small towns and villages. These are the areas where mobile broadband coverage is provided by mid-bands and sub-1 GHz bands. Catering to area traffic demand and ensuring indoor coverage are the key issues.

As an example of the issues faced in covering urban areas, in a typical Canadian city, 61% of land use is residential, institutional, industrial and commercial buildings. Transportation accounts for 32% and open spaces for 7%.[7] Although there are 5G indoor sites, not all buildings have them and therefore 5G coverage is provided from outdoor sites. Therefore mobile operators need substantial amounts of sub-1 GHz spectrum to penetrate deep into buildings to deliver consistent 5G speed coverage.

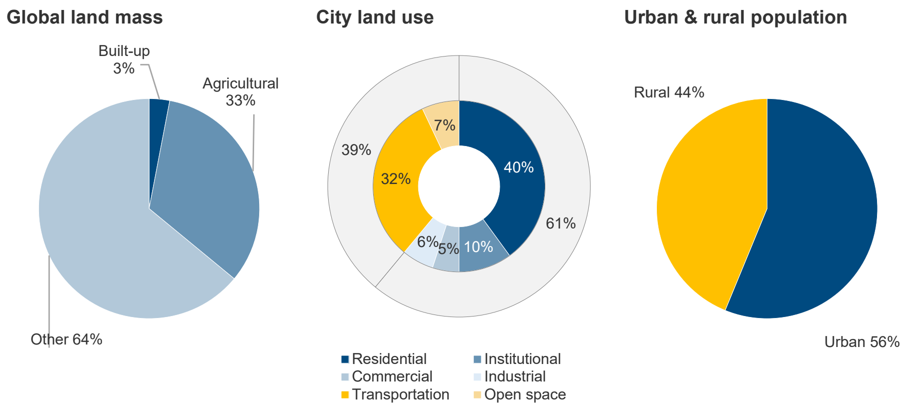
At the end of 2020, 56.2%[8] of the world's population lived in cities.[9] The remaining 43.8% of the world's population lives in other built-up areas, such as rural small towns and villages, and a very small proportion in isolated houses. For this population in low- and middle-income countries (LMICs), mobile is often the only source of connectivity, with much of it provided by sub-1 GHz spectrum. Additional sub-1 GHz spectrum is therefore essential to provide 5G mobile broadband connectivity and eliminate the urban-rural digital divide.

Agricultural areas (rural areas where people live and work) make up around 33% of global landmass, and some of this area is intensively farmed. Covering such areas is challenging and if often achieved through base stations covering rural villages and roads.

Smart agriculture solutions have a key role to play in optimising resources, reducing emissions and averting a world food crisis. The deployment of smart agriculture solutions is making it crucial to cover large areas with mobile networks cost-effectively. Smart agriculture applications that rely on higher data rates, such as video-based crop analysis using drones, can only be deployed effectively if additional sub-1 GHz spectrum is made available.

[6] Bringezu, S. and Bleischwitz, R. (2009). *Sustainable Resource Management: Global Trends, Visions and Policies*.
[7] Clark, B.W., Wallace, J.K. and Earle, K.M. (2006). *Making Connections: Canada's Geography*.
[8] World Bank. (n.d.) "Population, total". World Bank Data.
[9] UN Department of Economic and Social Affairs. (2018). *World Urbanisation Prospects*.

Exhibit 5: Population and land use



Source: See footnotes 1 to 4.

6 Sub-1 GHz spectrum to deliver 5G in rural areas

6.1 Digital inclusion policy considerations

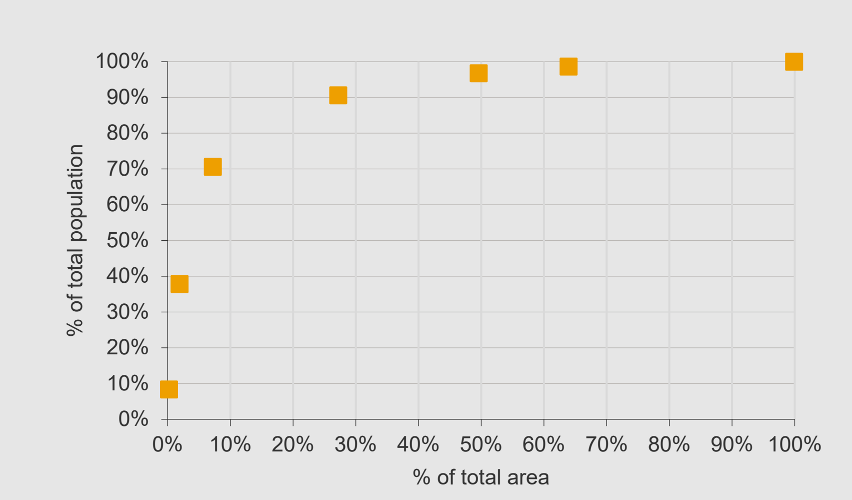
To reach rural connectivity goals, policy must address both the coverage gap (percentage of population not covered) and the usage gap (percentage of population covered but not using mobile broadband). In all countries, the usage gap is wider than the coverage gap. As of 2020, 92% of the world's population was covered by mobile internet, but only 51% was actually connected.[10] In other words, there is an 8% global coverage gap and a 41% usage gap. While lack of knowledge, skills and relevance partially explain this gap, affordability is a major factor, especially in LMICs, which account "*for more than 90% of the world's unconnected population and 98% of the uncovered population*".[11]

Exhibit 6 shows the cumulative population and land area in the UK. As population coverage nears 100%, more area will need to be covered for each incremental percentage. This general principle applies to virtually all countries: every additional per cent of population coverage is more expensive than the preceding per cent.

While network coverage obligations help to close the coverage gap, consumers and businesses in newly covered areas will not benefit from high volume data at high speeds unless mobile operators can reduce the cost per bit. Having more sub-1 GHz spectrum is essential to improve investment efficiency and thus reduce the cost per bit.

[10] GSMA. (2021). *The Mobile Economy 2021*. p. 41.
[11] Ibid., p. 46.

Exhibit 6: Population and land area in the UK



Source: Oughton, E.J. and Zoraida, F. (2017). "The cost, coverage and rollout implications of 5G infrastructure in Britain". *Telecommunications Policy*, 42(8), pp. 636–652.

6.2 5G drives the need for additional sub-1 GHz spectrum

There is a direct relationship between the amount of spectrum and the user experience in terms of DL and UL 5G speeds.

The amount of sub-1 GHz spectrum required to achieve voice coverage is small. However, when it comes to delivering sufficiently high data speed at the cell edge, the amount of sub-1 GHz spectrum is important because there is a direct relationship between the amount of spectrum and average user experienced data rate. This is critical to providing 5G in thinly populated areas, for example, along roads and agricultural areas, as well as deep indoors.

Tests have shown that a data speed of 600 Mbit/s can be achieved with 2x30 MHz in 700 MHz (band 28) if the user equipment (UE), such as a smartphone, is close to the base station (BS).[12] However, in rural areas, sub-1 GHz cell sites have a radius of about 10 km and data speeds are much lower at the cell edge.

Data speeds are already important for 4G (LTE-Advanced), and the ITU's IMT-2020 (5G) vision calls for a 10-fold increase in user-experienced speed compared to 4G. Today, operators typically aim to deliver at least 5 Mbit/s to 10 Mbit/s at the cell edge in rural areas, but this is expected to increase to 10 to 20 Mbit/s for 5G.

Making an additional sub-1 GHz can increase DL user-experienced speeds by 30 to 50%.

In locations where users are only covered by sub-1 GHz bands, capacity and hence user experienced speed increases proportionally to additional sub- 1 GHz spectrum deployed. Depending on the country, up to 210 MHz of sub-1 GHz spectrum may be available to mobile operators. In Region 1, 115 MHz of which is potentially available for assignment as mobile DL. In this scenario, making an additional 2x35 MHz available in the 600 MHz band (35 MHz DL, a 30% increase on 115 MHz) can increase DL user-experienced speeds by 30%. If 2x40 MHz additional sub-1 GHz spectrum is made available this can increase speeds by 35%. In countries where less sub-1 GHz is available, the making additional sub-1 GHz spectrum available for mobile can increase user experienced speeds by 50%.

We outline the different regional scenarios below for 600 MHz and a hypothetical North American scenario for additional low-band spectrum. Operators would deploy this additional spectrum on the existing sub-1 GHz cell-site grid using multiband antennas

[12] China Broadcasting Network Corporation Ltd. (CBN), Ericsson and UNISOC. (March 2021). The 700 MHz band n28 demo used Ericsson wireless equipment and DL 4-stream technology to achieve an average cell downlink rate of more than 600 Mbit/s on UNISOC's commercial customer premise equipment (CPE) with four receiver antennas.

and radios. This is, of course, much more cost-efficient and faster than building more cell sites.

Exhibit 7 shows four scenarios for Region 1, depending on whether the 700 MHz SDL band is available or not and depending on 2x35 MHz or 2x40 MHz of additional sub-1 GHz spectrum being made available. Sub-1 GHz capacity and with it user experienced speeds could increase by between 30 and 42%.

Exhibit 7: Region 1 impact of additional sub-1 GHz spectrum

Region 1 – DL spectrum (MHz)	700 SDL	No 700 SDL	700 SDL	No 700 SDL
900 FDD	35	35	35	35
800 FDD	30	30	30	30
700 FDD	30	30	30	30
700 SDL	20	0	20	0
Current total	115	95	115	95
Potential 600	35	35	40	40
Potential total	150	130	155	135
Increase	30%	37%	35%	42%

Source: Coleago

Exhibit 8 shows the potential impact for Latin America in ITU Region 2, and Region 3, Asia Pacific for 2x35 MHz and 2x40 MHz. In Asia Pacific, The APT Wireless Group (AWG) has initiated discussions regarding a 2x40 MHz band plan which overlaps with the US 600 MHz (n71). A 3GPP specification is expected by the end of 2022. The amount of sub-1 GHz spectrum identified for mobile in these regions is less than in Region 1 and hence the impact on making additional spectrum available would be greater, potentially delivering a 50% uplift in sub-1 GHz area traffic capacity.

Exhibit 8: Region 2 (LatAm) and 3 impact of additional sub-1 GHz spectrum

Region 2 (LatAm) & 3 (APAC) – DL spectrum (MHz)	A	B
850 FDD	25	25
700 FDD	45	45
900 FDD	10	10
Current total	80	80
Potential 600 FDD	35	40
Potential total	115	120
Increase	44%	50%

Source: Coleago

Exhibit 9 shows two speculative scenarios for North America. In the US and Canada the 600 MHz band is already used for mobile (band n71) with 2x35 MHz. The amount of spectrum in band n71 was the result of an auction which matched the willingness of broadcasters to relinquish spectrum at prices mobile operators were prepared to pay. According to FFC documents[13] for the 600 MHz auction, an auction outcome with 2x50 MHz would have been possible, extending the band further downwards. In the hypothetical scenarios for an additional 15 MHz and 30 MHz of DL spectrum being made available below 617 MHz, DL speeds could increase by 14 or 29% respectively.

[13] Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, DA/FCC #: FCC-14-50, Docket/RM: 12-268, 2014

Exhibit 9: Region 2 (North America) impact of additional sub-1 GHz spectrum

Region 2 - North America – DL spectrum (MHz)	A	B
850 FDD	25	25
700 FDD	35	35
700 SDL	10	10
600 FDD	35	35
Current total	105	105
Potential 600	15	30
Potential total	120	135
Increase	14%	29%

Source: Coleago

6.3 The spectrum and site trade-off in rural areas

There is a trade-off between the number of sites that need to be built to cover an area and the amount of sub-1 GHz spectrum available to achieve a coverage target. There are two scenarios:

- Performance target in existing coverage area**:** Within an existing coverage area, additional sub-1 GHz can be deployed on the low-band grid. This improves performance in terms of user-experienced speed at the cell edge. In the absence of additional sub-1 GHz spectrum, additional in-fill sites would need to be built to achieve the same performance target.
- Greenfield coverage: When extending the coverage area of a network to where there was previously no mobile coverage, then the more spectrum is available, the fewer the sites that will be needed to achieve a given cell edge performance target. This scenario is particularly relevant for countries pursuing coverage targets, such as population coverage, road coverage or land area coverage. The benefit is likely to be greatest in LMICs, especially in Africa where a higher percentage of the population is uncovered and cost efficiency is a significant issue.

Performance targets in an existing coverage area

Cell edge throughputs of at least 6 Mbit/s in the DL and 2 Mbit/s in the UL are needed to meet minimum requirements for HD streaming, online education and video conferencing. Operators are aiming for rural cell edge speeds between 10 to 30 Mbit/sfor 5G to ensure that the average user experienced data rate is sufficient for future services demand.

Cell edge speed is typically calculated for a single user (i.e. assuming there is only one user in a cell). For a given amount of spectrum and MIMO configuration, the greater the distance from the base station, the lower the single user cell edge speed. The single user cell edge speed can be considered a proxy for sub-1 GHz area traffic capacity.

However, user-experienced speed depends on the number of simultaneous users (i.e. area traffic demand). Therefore, user-experienced speed in an area where sub-1 GHz provides coverage depends on:

- The single-user cell edge speed target;
- The amount of sub-1 GHz spectrum available; and
- Area traffic demand.

In rural areas, MNOs typically install both sub-1 GHz bands and mid-bands on the same site. Exhibit 10 below provides an illustration of this. The inner dark blue circle represents the mid-band coverage area and the outer light blue ring represents sub-1

GHz coverage area. Operators ensure mid-band spectrum is used where available so that sub-1 GHz capacity is available where mid-bands coverage does not reach.

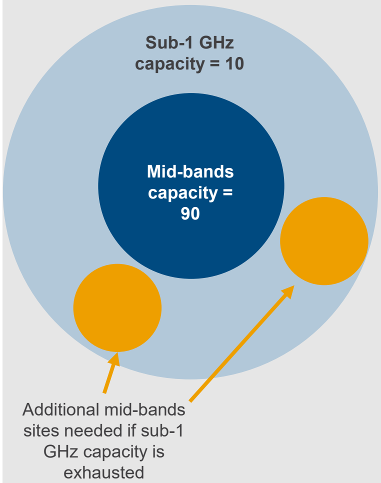
As mentioned in section 4, mid-band capacity is far greater than sub-1 GHz capacity. Operators can install more mid-bands to create additional capacity, but this only benefits users located in the mid-band coverage area (the dark blue circle). As 5G traffic increases, traffic loading over the entire area increases, i.e. also in the area that can only be served with sub-1 GHz spectrum (the outer light blue ring). This means user-experienced speed for users located in the outer ring degrades. There are two options to ensure these users still experience a reasonable speed:

- If additional sub-1 GHz spectrum is made available, it can be added to the site to increase capacity in the outer ring; or
- If there is no additional spectrum, one or two additional capacity cell towers with mid-bands will need to be built to increase capacity in the outer ring.

Building a new cell tower is about 5 to 10 times more expensive than adding additional sub-1 GHz to an existing rural site.

Building a new cell tower is about 5 to 10 times more expensive than adding additional sub-1 GHz to an existing rural site[14]. Delivering consistent 5G speed coverage in rural areas cost-effectively therefore depends on sub-1 GHz spectrum.

Exhibit 10: Running out of sub-1 GHz capacity: an illustration



A conceptual illustration

An operator has deployed all available sub-1 GHz spectrum on a site as well as mid-bands spectrum. The combined mid-bands and sub-1 GHz capacity is 100.

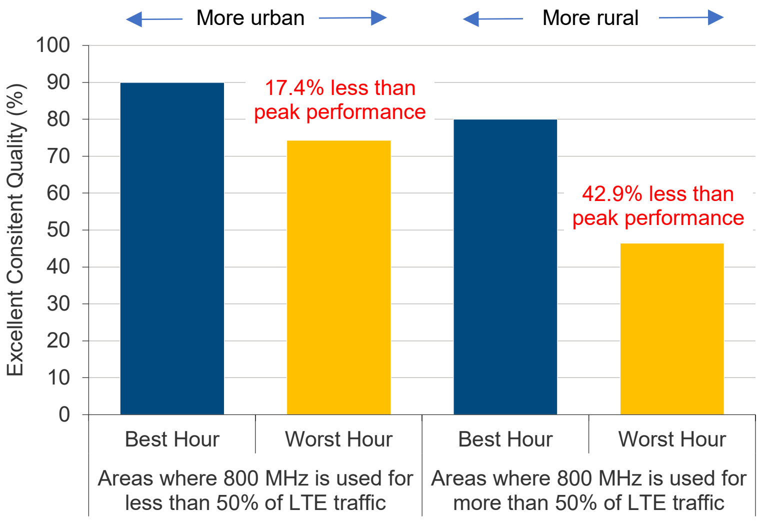
- Let's assume total traffic increases to 80, which is below the total capacity.
- However, traffic is distributed between sub-1 GHz bands and mid-bands as follows:
  - 20% of traffic can only served by sub-1 GHz. Therefore, sub-1 GHz traffic demand is 80 x 20% = 16
  - 80% of traffic can be carried on mid-bands , 80 x 80% = 64
- The sub-1 GHz traffic demand of 16 is 60% higher than the sub-1 GHz capacity of 10.
- If no additional sub-1 GHz spectrum is made available, to maintain the user experienced speed, additional sites with mid-bands would have to be added, which will reduce the percentage of traffic that can only be carried on sub-1 GHz.
- However, if more sub-1 GHz spectrum is obtained, this could be deployed on the existing site and would increase sub-1 GHz capacity, thus avoiding the need to build additional sites.

Source: Coleago.

Exhibit 10 illustrates that higher traffic leads to congestion in areas covered only by sub-1 GHz spectrum. This effect has been measured by Tutela[15] in EE's network in the UK, which shows that an area that relies more heavily on sub-1 GHz for coverage experiences a disproportionate slow-down in data speeds with higher traffic. The measurements shown in Exhibit 11 compare the user experience in the best hour (least congested) with the worst hour (most congested).

[14] Data gathered from Coleago's work with mobile operators world-wide
[15] Tutela, March 2021.

Exhibit 11: Performance degradation in peak usage hours



Source: Tutela.

In the absence of additional sub-1 GHz spectrum, additional sites and backhaul links would need to be built to maintain a 5G user experience. Coleago found that building sites and backhaul in rural areas is four to six times[16] more expensive than in urban areas. In contrast, if additional sub-1 GHz spectrum is available, this can be added to the existing cell site at a relatively low cost.

Greenfield coverage

Bringing mobile broadband coverage to uncovered areas is increasingly expensive because as population density decreases, the cost of coverage per user increases. The main cost driver is the number of cell sites required to cover a new (greenfield) area with sufficient user-experienced speed.

Operators design networks to deliver a particular cell edge speed target and, as mentioned earlier, at a given cell edge speed target, the cell radius and inter-site distance are determined by the amount of sub-1 GHz spectrum deployed on cell sites. The more sub-1 GHz spectrum is available, the fewer sites needed to cover a new area.

Exhibit 12 shows the cost reduction in greenfield coverage if an operator receives an additional 2x10 MHz or 2x20 MHz of spectrum in 600 MHz, assuming the operator already holds 2x10 MHz in each of the 700, 800 and 900 MHz bands. The calculations shown are for two scenarios:

- Scenario 1: a single user and near line of sight. The single user calculation shows the theoretical limit from a propagation perspective. However, in a covered area of 2,000 km^2, even with a population density of only one person per km^2, there would still be 2,000 users in the area, many of which would rely on sub-1 GHz capacity. This shows that the limiting factor in cell range (inter-site distance) is not the theoretical cell range, but a network design that considers both propagation characteristics and cell loading, which is driven by population density.

[16] Source: Coleago research. Rural sites are typically high towers whereas urban sites use rooftops or poles. In urban areas, fibre tends to be near the site, whereas in rural areas either expensive microwave links need to be used or fibre needs to be brought in over long distances. There may be no grid power near rural sites.

With an additional 2x10 MHz, 21% fewer cell sites are required to cover the same area and with an additional 2x20 MHz, 33% fewer sites are required.

- Scenario 2: a rural cell range typically found in cellular networks. The smaller, real-world cell range is a realistic value for policymakers to assess the benefit of providing additional sub-1 GHz spectrum to lower the cost of rural coverage. Data shows the impact of additional sub-1 GHz spectrum on the size of the coverage area. With an additional 2x10 MHz, 21% fewer cell sites are required to cover the same area, and with an additional 2x20 MHz, 33% fewer sites are required. This is a realistic indication of the site and cost savings for rural 5G coverage if additional sub-1 GHz spectrum is made available.

Exhibit 12: Rural coverage cost reductions from additional sub-1 GHz spectrum

	No additional spectrum	Plus 2x10 MHz of 600 MHz	Plus 2x20 MHz of 600 MHz
Spectrum	900 MHz – 2x10 MHz 800 MHz – 2x10 MHz 700 MHz – 2x10 MHz	900 MHz – 2x10 MHz 800 MHz – 2x10 MHz 700 MHz – 2x10 MHz 600 MHz – 2x10 MHz	900 MHz – 2x10 MHz 800 MHz – 2x10 MHz 700 MHz – 2x10 MHz 600 MHz – 2x20 MHz
Cell edge downlink speed	20 Mbit/s	20 Mbit/s	20 Mbit/s
Single-user cell range[1]	27.0 km	30.5 km	33.1 km
Single-user cell area	1,897 km^2	2,412 km^2	2,843 km^2
Typical cell range[2]	9.0 km	10.2 km	11.0 km
Typical cell area	210 km^2	269 km^2	316 km^2
Reduction in cell sites	–	21%	33%

Source: Coleago.

Notes: 1. Simulation assumes a single cell-edge user per site; rural near line of sight, 50m 40W base station and using the Okumura-Hata propagation model; SINR performance simulations for 4x2 MIMO 64 QAM.

2. The typical cell range is how operators design their network, taking into account non-line of sight, terrain and cell loading.

Lowering the cost of meeting rural coverage objectives

There is a link between the amount of sub-1 GHz spectrum available to be deployed and cost of service

Given the cell-site savings opportunity, the more sub-1 GHz spectrum is available the more cost-efficient is the provision of sufficient area traffic capacity and, with it, the required user-experienced speed in rural areas. Network capex and the ensuing cost of service are impacted by the cost of building area traffic capacity. Therefore, there is a link between the amount of sub-1 GHz spectrum available to be deployed and cost of service.The full benefit of 5G is only realised if operators can reduce the cost per bit which will allow consumers to benefit from higher data volumes in an affordable way.

6.4 5G coverage along transport routes

For regulators, 5G coverage along roads and other transport links is an important policy goal. Inter-site distances along roads in non-populated areas are largely determined by the range of sub-1 GHz spectrum for a given cell edge and cell average speed target.

To illustrate the reliance on sub-1 GHz spectrum for rural highway coverage, we provide two examples. Exhibit 13 shows coverage of a rural stretch of the Trans-Canada Highway using 850 MHz. Exhibit 14 shows an example of a 400 km stretch of rural highway in the Asia-Pacific region.

On long stretches of rural highways, it is not economically feasible to provide continuous coverage with mid-band spectrum.

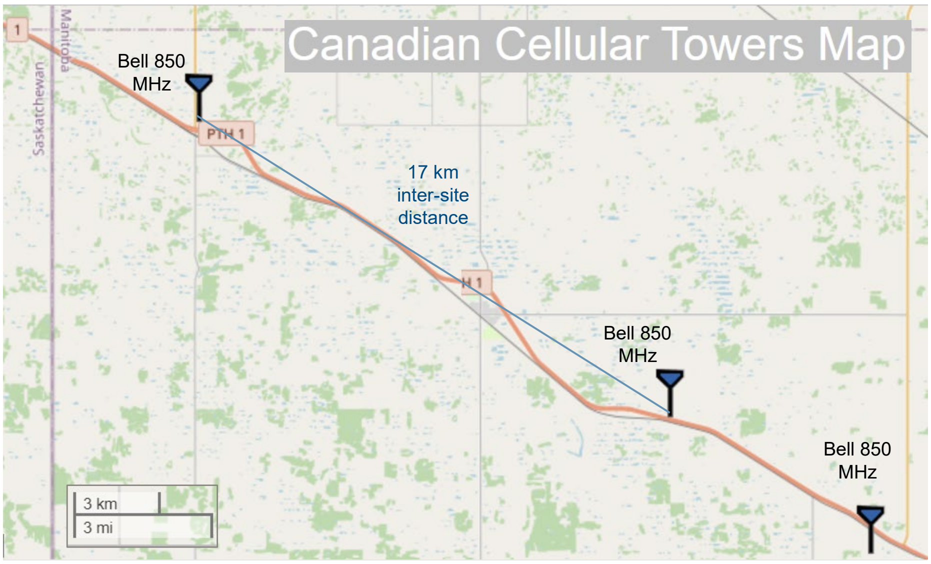
Both examples clearly show that on long stretches of rural highways, it is not economically feasible to provide continuous coverage with mid-band spectrum, and that sub-1 GHz spectrum must provide sufficient bandwidth for connected vehicles. In a 5G environment, traffic demand from connected vehicles and passengers in those vehicles will increase substantially. While mid-bands added to existing sites can handle some of the traffic demand, mid-band cell range is insufficient to cover the inter-site distance between existing sub-1 GHz cell towers. The required 5G user-experienced data rate can then be delivered by either reducing the inter-site distance and/or by deploying more sub-1 GHz spectrum.

Building additional sites along roads through rural areas is very costly. Depending on the country, these sites, including power and backhaul, can cost between US$400,000 and $700,000 each. Adding another sub-1 GHz radio to an existing site, including civil works, might cost $30,000 to $60,000.

The need for 5G capacity along roads will increase sharply to serve the connected vehicle use case. This spectrum need is driven by general eMBB use cases, including information, entertainment and diagnostics, as well as road safety-related communication.

A 5GAA study that looked at the spectrum needs of use cases for intelligent transport systems (ITS) and advanced driving using cellular vehicle-to-everything (C-V2X) technologies concluded that "*[a]t least 50 MHz of additional service-agnostic low-band (< 1 GHz) spectrum would be required for mobile operators to provide advanced automotive V2N services in rural environments with affordable deployment costs.*"[17] This excludes the entertainment use case.

Exhibit 13: Road coverage with 850 MHz



Source: Canadian Cellular Tower Map.

Exhibit 14: Sub-1 GHz rural highway coverage

This example from a country located in Asia-Pacific refers to a section of an inter-capital highway that runs through largely uninhabited countryside interspersed with small communities with populations typically not more than 100 persons.

The section of highway is more than 400 km in length. The daily road traffic is approximately 1,850 vehicles, of which 80% (350) are light vehicles.

This section of highway is covered by 10 sub-1 GHz base stations, with an average site spacing of 39 km. However, there are four sites with an inter-site distance of between 50 and 70 km. Given the large inter-site distance, mid-band spectrum cannot be used to provide contiguous speed coverage.

Source: Mobile operator in the Asia-Pacific region

[17] 5G Automotive Association (5GAA). (2021). *Study of spectrum needs for safety-related intelligent transportation systems – day 1 and advanced use cases*.

6.5 Smart agriculture

Mobile regulatory policy rightly focuses on coverage that delivers the greatest socio-economic benefit: population, road and railways and transport hubs. As a result, in most countries, the percentage of agricultural area covered is significantly lower than the percentage of population covered.

Smart agriculture requires coverage to be provided both over large areas and vertically coverage for drone connectivity. This is much more challenging than providing coverage along roads.

Smart agriculture requires coverage both over large areas and vertically for drone connectivity. This is much more challenging than providing coverage along roads. While road coverage needs to be linear, it is sufficient to build one additional mid-band site between existing cell sites to compensate for the lack of capacity provided by sub-1 GHz spectrum. However, to cover an area rather than simply providing coverage along a line, three additional sites would be required. In addition, the cost of roadside in-fill sites is much lower than for sites away from the road where there is unlikely to be fibre or power.

While many agricultural applications require only a low data rate, such as sensors, video-based applications require data rates as high as 6 Mbit/s for HD streaming or 15 Mbit/s for 4K HD. The larger the area over which this speed can be provided, the more useful the applications for smart agriculture.

Covering all agricultural areas is not economically feasible, but deployment of more sub-1 GHz spectrum at an existing site increases the distance to the cell edge where the network can deliver the minimum speed the application requires. This means additional sub-1 GHz spectrum is a key element in enabling 5G agricultural applications.

Exhibit 15: Drone-enabled precision farming

Source: Coleago.

7 Sub-1 GHz spectrum for consistent coverage in built-up areas

7.1 Speed coverage for enhanced mobile broadband

Sub-1 GHz spectrum is essential to provide eMBB speed coverage in hard-to-reach places, such as deep indoors or narrow alleys.

The requirement for enhanced mobile broadband (eMBB) is a user-experienced data rate of 100 Mbit/s DL and 50 Mbit/s UL. Sub-1 GHz spectrum is essential to provide eMBB speed coverage in hard-to-reach places, such as deep indoors, narrow alleys in built-up areas and in the shadow of buildings or other obstacles.

A radio signal loses strength as it travels from an outdoor base station through a building to reach the indoor user. The loss experienced varies by the type of external and internal construction, as well as the frequency range.

Depending on the city, town or village, there can be many hard-to-reach outdoor spaces, such as narrow alleys, curved village streets and courtyards, as shown in Exhibit 16. Such spaces are more prevalent in, for example, the historic areas of towns and villages.

Exhibit 16: Hard-to-reach outdoor spaces

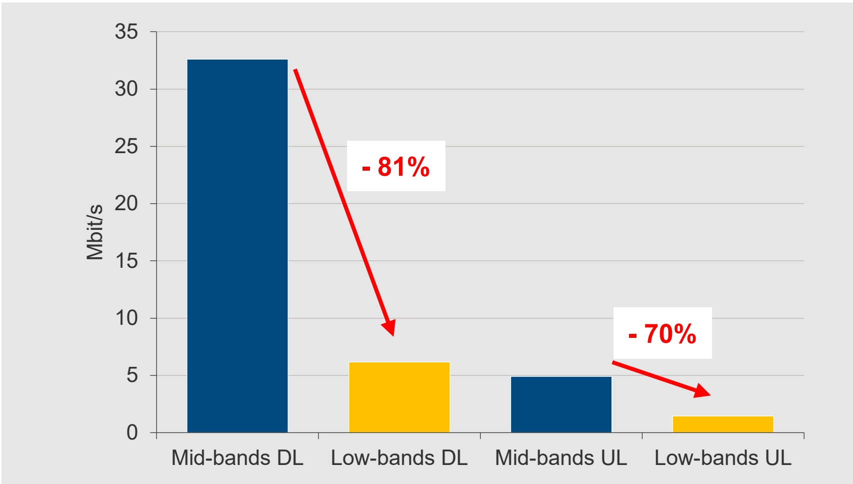
Source: Coleago.

Therefore, in built-up areas, a significant proportion of area traffic demand can only be carried by a limited amount of low-band spectrum held by MNOs. This is evidenced by traffic data that Coleago gathered and analysed from mobile operators. Although in cities, mobile networks provide continuous coverage and inter-site distances are short, around 15% of traffic flows through sub-1 GHz spectrum.

Real-world operator data demonstrated that:

- Eighty per cent of network congestion in urban areas is in low-band;
- Low-band carries 10% to 20% of traffic in dense urban areas; and
- The user-experienced data rate in the busiest hours of the day using low-band can be 80% slower (DL) and 70% slower (UL) than mid-band.

Exhibit 17: Low-bands vs. mid-bands speeds in cities in a European country



Source: European mobile network operator.

Operator data (see Exhibit 18 below) also showed that traffic per MHz in a 4G environment was 50% higher in low-bands than mid-bands with holdings of 2x10 MHz in low-band and 2x35 MHz in lower-mid bands.

Exhibit 18: Sub-1 GHz vs. mid-band spectrum and traffic

Range	Spectrum holding	% of traffic	% of traffic per MHz
Low-bands	2x10 MHz	30%	3%
Mid-bands	2x35 MHz	70%	2%

Source: Measurements in several mobile networks.

These examples are typical for MNOs around the world and provide evidence that the relative lack of sub-1 GHz spectrum is the cause of the speed challenge indoors and in other hard-to-reach places.

In this context, the growth of 5G data traffic is a problem. While network densification and additional indoor cells will help to address this, demand will grow for capacity beyond the reach of the mid-bands. For these indoor spaces, additional sub-1 GHz spectrum is vital to consistently meet the ITU-2020 requirement of an average user experienced data rate of 100 Mbit/s DL and 50 Mbit/s UL[18], even deep indoors and in other hard-to-reach places.

Outside cities, as the population density decreases, inter-site distances tend to increase. As a result, cell sites are typically located further away from buildings and the indoor speed coverage problem increases. Given that mid-bands do not propagate into buildings as well as sub-1 GHz spectrum, there is an even greater reliance on sub-1 GHz spectrum to deliver user-experienced speed consistent with the 5G vision indoors in rural areas. Making additional sub-1 GHz spectrum available would help to narrow the user-experienced speed gap.

A study[19] carried out in 2018 by the UK communications regulator Ofcom quantifies the benefit of indoor speed coverage using sub-1 GHz. The study examined the reach this band could provide over mid-bands (specifically 1800 MHz) for “shallow” and “deep” indoor locations. A “shallow” indoor environment was modelled, representing indoor areas close to windows or external walls, with a loss in the range of 10–15 dB, as well as a “deep” indoor environment with a penetration loss in the range of 25–30 dB. The study concluded that:

“The same 2x20 MHz of 1800 MHz network is not quite able to match the performance of a 700 MHz network with a 10 MHz carrier (despite having a denser site grid and twice the carrier bandwidth). More specifically:

- *lower frequency spectrum (2x10 MHz of 700 MHz) allows operators to provide a given level of customer experience to a larger share of indoor locations than a network based on 1800 MHz (2x20 MHz of 1800 MHz), particularly in deep indoor locations;*
- *in the case of deep indoor locations, a network based on 2x10 MHz of 700 MHz can outperform a network with 2x20 of 1800 MHz (i.e. with twice the bandwidth).”*

If an additional 2x35 MHz of sub-1 GHz spectrum is made available for mobile, this could increase indoor speeds by 30%.

If an additional 2x35 MHz of sub-1 GHz spectrum is made available for mobile, this could increase indoor speeds by 30% and an additional 2x40 MHz could deliver a 35% uplift in indoor speeds.

7.2 Capacity for ultra-reliable and low-latency communication

Ultra-reliable and low-latency communication (uRLLC) is one of the three IMT-2020 (5G) usage scenarios.

While low-latency applications typically use higher frequencies, in many locations, reliability depends on low-band capacity. Reliability requires services to function at levels required by the application or use case. Adequate speed coverage is a precondition for reliability, and the fewer speed coverage not-spots in a city – indoors or outdoors – the more reliable a service will be. Since additional sub-1 GHz spectrum, particularly below 700 MHz, increases area traffic capacity deep indoors and in other hard-to-reach places, there is a direct link between making additional sub-1 GHz spectrum available and the ‘reliability’ aspect of the uRLLC use case.

It is unlikely that all uRLLC applications, notably smart cities, can be delivered without making additional sub-1 GHz spectrum available for 5G mobile networks.

[18] Report ITU-R M.2441-0 (11/2018)
[19] Ofcom, “Award of the 700 MHz and 3.6-3.8 GHz spectrum bands”, Annexes 5-18 – supporting information , p. 121

8 Sub-1 GHz spectrum for legacy technology

A proportion of low-band capacity will continue to be set aside to support residual 2G and 3G traffic, including legacy M2M. Since the bandwidth is not available for mobile broadband, additional low-band spectrum will be required to compensate. This is a minor issue in markets that transition quickly to all VoLTE/VoNR, but it could have an impact in LMICs for the rest of the decade. While mid-band spectrum may be refarmed quickly to 4G and 5G, the need to maintain a basic circuit-switched voice coverage layer means that sub-1 GHz spectrum will be slowest to be refarmed fully to 4G/5G.

While the amount of sub-1 GHz spectrum to be retained for 2G/3G is not significant, given the relatively small amount of sub-1 GHz spectrum available it still has a material impact. Even if an operator only needs 2.4 MHz for 2G voice, due to a 5 MHz channel bandwidth minimum for 5G, 2x5 MHz may not be available for 4G/5G. In a four-operator market, the total "loss" to 4G/5G would be 2x20 MHz.

It is the same situation in rural areas where sub-1 GHz spectrum is needed most for 5G, but needs to be retained for 2G/3G for longer.

9 Sub-1 GHz spectrum as a cost-efficient capacity solution for 5G

Increasing sub-1 GHz spectrum capacity affects the cost-efficiency of 5G. This relates to the amount of spectrum deployed in a single band and the number of sub-1 GHz bands available.

Increasing spectrum can impact costs in four ways:

- Deployment of multiple sub-1 GHz frequency bands in a single radio and antenna reduces the cost per band deployed;
- Deployment in a wide channel reduces the cost per MHz deployed and increases bandwidth utilisation;
- 4T4R MIMO deployment in a wider band can improve efficiency and reduce costs; and
- A single cell tower can serve more FWA connections with additional bandwidth, thus lowering the cost per FWA connection.

Multiple bands in a single radio and antenna

With the evolution of radio access technologies from 4G and 5G, multi-low-band deployments are becoming a key trend, addressing both the growth in data traffic and higher customer expectations of the user experience. The possibility of combining three low-bands within a single radio and antenna substantially increases cost-effectiveness and, therefore, investment efficiency.

If additional sub-1 GHz frequencies were made available, capital expenditure on deployment and operating costs would not increase proportionally to the number of bands.

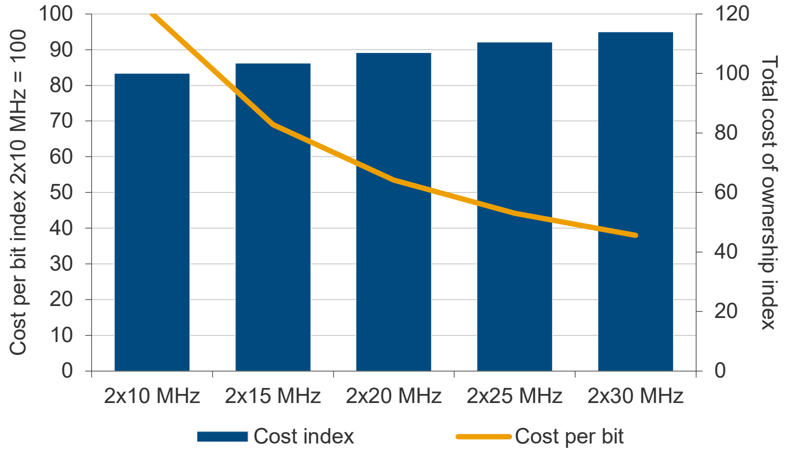
Although equipment would require swapping out, the total cost of ownership of 4T4R dual-band radio and antenna is only 50%[20] higher than a single-band configuration. This means that if additional sub-1 GHz frequencies were made available, the deployment capital expenditure (capex) and network operating costs would not increase proportionally to the number of bands. The more low-band frequencies there are available for deployment in a single radio, the more efficient the investment.

[20] Based on vendor information.

Deploying in a wide channel to reduce the cost per MHz deployed

5G in sub-1 GHz can be deployed in a wider channel than 4G. With a recent addition to the 3GPP specification for Band 28 (700 MHz APT), the maximum channel bandwidth is now 30 MHz instead of 10 MHz[21]. Assigning a wider band to an operator to use in a single radio can reduce the cost per MHz deployed by 62%. This is particularly significant for delivering affordable broadband in rural areas (see Exhibit 19).

Exhibit 19: Cost-efficiency in wider band deployment



Source: Coleago.

Deploying in a wide channel to increase bandwidth utilisation

Sub-1 GHz spectrum is scarce compared to mid-bands, making it vital to maximise spectral efficiency. The wider the channel, the greater the bandwidth utilisation.

In a 2x10 MHz deployment, just 86.7% of bandwidth is used for data throughput, but in a 2x30 MHz wide deployment channel it is 93.7%, a gain of 8.1%. Given the scarcity of sub-1 GHz spectrum, this is material.

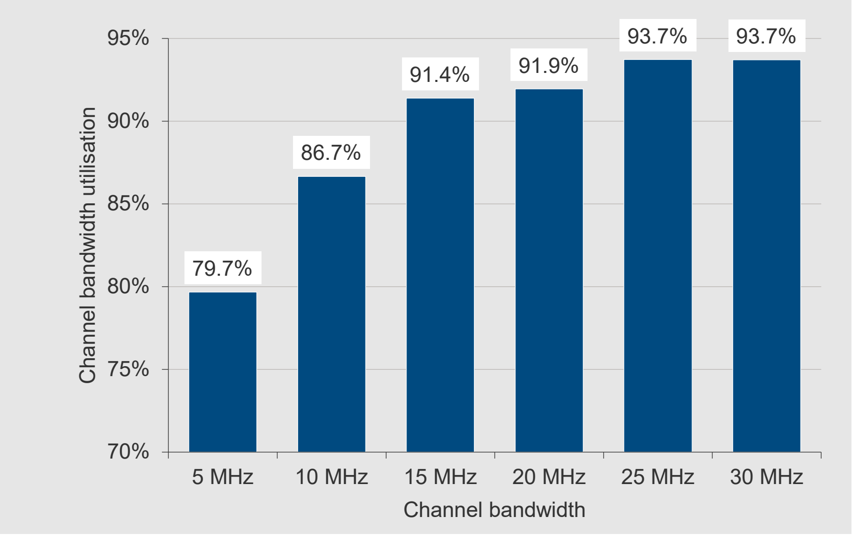
4G and 5G transmission technology is structured into resource blocks. These resource blocks have fixed width which may not fit exactly into a 5 MHz wide channel and thus some bandwidth is not used. This unused portion of bandwidth declines with wider channels. Exhibit 20 below illustrates this effect. In a 2x10 MHz deployment only 86.7% of bandwidth is used for data throughput, but in a 2x20 MHz wide deployment channel, this increases to 91.9%, a gain of 5.7%. With 2x30 MHz utilisation increases to 93.7%, a gain of 8.1%.

In addition, performance gains in larger bandwidths come from better performance of frequency selective scheduling, larger resource pool with better optimisation potential, and less relative signalling overhead in wider carriers. These additional gains are in the order of 5 - 10% for a 20 MHz wide channel compared to a 10 MHz wide channel. This therefore brings overall efficiency gains for a 2x20 MHz wide channel compared to 2x10 MHz to 10 - 15%. Given the scarcity of sub-1 GHz spectrum, this is significant.

If additional sub-1 GHz spectrum is made available, bands could be redistributed (see section 10) to allow an operator to hold 2x20 MHz in a band or even 2x30 MHz.

[21] 3GPP TS 38.104 V17.1.0 (2021-03), (Release 17)

Exhibit 20: Channel bandwidth utilisation



Source: Coleago.

Cost-efficient deployment of 4T4R MIMO

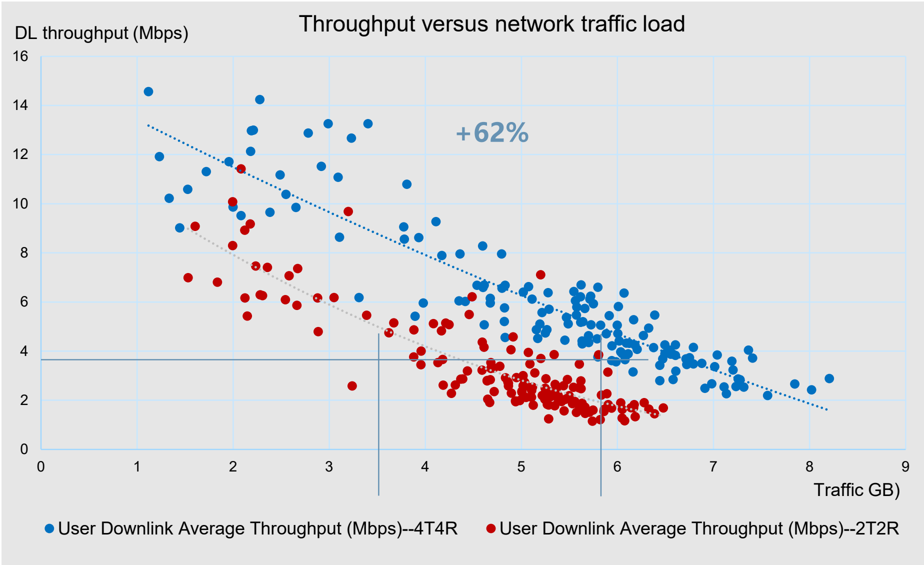
Given the scarcity of low-band spectrum, it is vital to use it more efficiently. Cell-edge users, especially those indoors, place a disproportionate burden on mobile networks because they often cannot be reached with the higher bands and tend to cause low-band congestion.

Even though smartphones can only support two low-band antennas (due to size constraints), deploying 4T4R MIMO technology in sub-1 GHz spectrum allows MNOs to dramatically increase cell-edge capacity and performance. Deploying MIMO is costly, so the more MHz that is available the more investment efficiency will improve.

Low-band 4T4R boosts capacity and performance at the cell edge. Moreover, where low-band plus mid-band spectrum are co-deployed, as is common in urban areas, low-band 4T4R improves the experience for all users, with cell-edge users on low-bands and users in the middle of the cell primarily on mid-bands.

Addressing the cell-edge issue with low-band 4T4R allows mid-band resources to be used more efficiently, leading to higher output for all users. Tests performed on commercial 1800 MHz plus 900 MHz LTE networks suggest that low-band 4T4R can produce a net gain of 69% in throughput and 62% in capacity, relative to low-band 2T2R.

Exhibit 21: Low band 4T4R throughput gain vs. 2T2R



Source: Operator and tests.

Exhibit 22 shows the relative cell edge speed that can be achieved with 700 MHz spectrum, depending on:

- The amount of spectrum;
- The configuration of MIMO on network base stations;
- The MIMO configuration of the UE; and

The base (100%) is for 2x10 MHz with a 2T2R configuration with a 5 Mbit/s speed target. Comparing the 5 Mbit/s and 10 Mbit/s columns, it is clear that a higher speed target reduced the cell range.

Additional sub-1 GHz spectrum reduces the per MHz cost of deploying 4T4R MIMO.

This can be compensated for by investing in MIMO. However, this investment is the same regardless of whether 2x10 MHz or 2x30 MHz are available per operator. Adding 2x20 MHz to bring the total to 2x30 MHz per operator leverages the benefit of 4T4R MIMO and provides a cost-effective way to deliver adequate 5G speeds in rural areas.

The importance of a wide channel in sub-1 GHz spectrum is illustrated by the following statement from a leading operator in Europe:

"Regarding 5G network design criteria for outdoor rural coverage, we currently use 3 Mbit/s indoor as target so would recommend to use 5 Mbit/s for outdoor. We don't expect 3 Mbit/s target to change, especially when considering use of a low band 10 MHz FDD channel."[22]

Clearly these speeds are well below what is required to deliver an adequate 5G user-experienced speed, and while operators play their part by investing in 5G, including MIMO, policymakers and regulators must also play their part by making additional sub-1 GHz spectrum available.

The cost issue is important, especially for countries with significant rural populations spread over large areas. For LMICs using additional sub-1 GHz spectrum, this is the only economically feasible solution to achieving rural broadband coverage objectives.

[22] European mobile operator, January 2022.

Exhibit 22: Relative rural 5G cell edge speed depending on spectrum and MIMO

Sub-1 GHz spectrum	Network MIMO configuration	UE MIMO configuration	Relative cell edge speed
2x10 MHz	2T2R	2T2R	100%
2x10 MHz	4T4R	2T2R	150%
2x10 MHz	4T4R	4T4R	200%
2x20 MHz	2T2R	2T2R	200%
2x20 MHz	4T4R	2T2R	300%
2x20 MHz	4T4R	4T4R	400%
2x30 MHz	2T2R	2T2R	300%
2x30 MHz	4T4R	2T2R	450%
2x30 MHz	4T4R	4T4R	600%

Source: Huawei, adapted by Coleago.

FWA for isolated rural buildings

In rural regions where wireless is the only connectivity option, sub-1 GHz spectrum has a role to play in providing internet access to isolated buildings.

The relatively small amount of sub-1 GHz spectrum available compared to mid-band spectrum means there is not enough capacity for 5G FWA use, in rural areas where wireless is the only connectivity option, sub-1 GHz spectrum has a role to play in providing internet access to isolated rural buildings, such as farms. This is not only the case in LMICs, but also in countries with a developed telecoms infrastructure.

The economics of delivering 5G FWA to rural buildings depends on the amount of spectrum available. The more sub-1 GHz spectrum that can be deployed on a single cell tower, the more FWA customers that can be served from that tower. This reduces the cost per FWA connection. In most cases, building 5G coverage in sparsely populated areas is not economically viable and subsidies are required. The more sub-1 GHz spectrum that is made available, the lower the subsidies needed.

For example, following assignment of 600 MHz spectrum (band 17) to mobile in the US, in January 2019, T-Mobile announced the launch of the Coolpad Surf, a 600 MHz mobile hotspot designed specifically to bring service to rural areas. This is just one example of how additional sub-1 GHz spectrum can be used to improve rural connectivity.

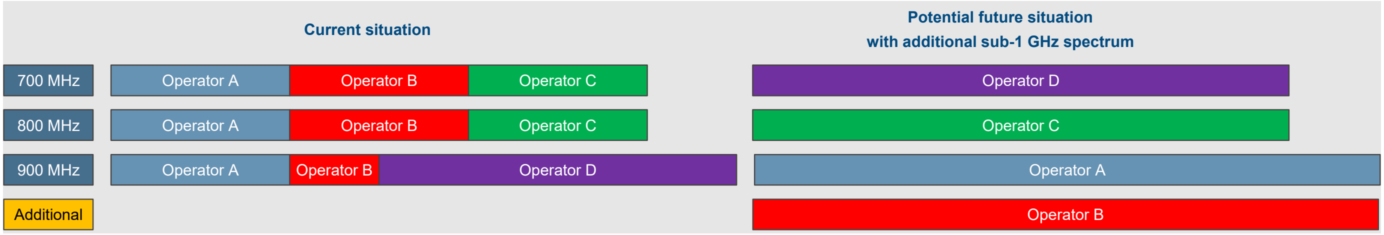
One of the advantages of FWA routers is that they do not have the size constraints that limit the number of sub-1 GHz antenna in smartphones. Sub-1 GHz FWA routers can be equipped with four antennas, which means that 4T4R is available both in the network and in the UE, which results in a lower cost per Mbit/s of deployed bandwidth.

10 The opportunity for sub-1 GHz bands reorganisation

In most markets, operators hold small amounts of spectrum in each of the sub-1 GHz bands assigned in that market. This is something that developed over time and is necessary for a level playing field. However, depending on the market, it may be possible to defragment sub-1 GHz holdings over 7 to 10 years.

Exhibit 23 shows the current sub-1 GHz holdings for each mobile operator in a four-operator market. Assuming an additional 2x35 MHz becomes available, each operator could be assigned one entire frequency band. 3GPP specifications for 30 MHz wide channels already exist for 700 MHz Band 28 and wider channel specifications are likely to be introduced for other sub-1 GHz bands. A wider band allocation would increase both spectral and investment efficiency.

Exhibit 23: Potential defragmentation in a four operator market



Source: Coleago.

11 Additional sub-1 GHz spectrum versus carrier aggregation

Sub-1 GHz and mid-band CA is a good technical solution to expanding the cell range of the mid-bands because UL is the limiting factor in the cell range. However, CA does not extend the cell range of mid-bands to sub-1 GHz bands and does not extend the cell range of sub-1 GHz bands.

Sub-1 GHz inter-band CA is not supported in UEs as they typically have a single low band radio which can only be tuned to one carrier frequency at a time. This means UEs can support up to 30 MHz contiguous, but not multiple 10 MHz carriers in different sub-1 GHz bands.

Sub-1 GHz CA is not will never be a substitute for making additional sub-1 GHz spectrum available.

Even if in a future development CA of sub-1 GHz bands became feasible, performance would be lost if two non-contiguous channels are aggregated, as shown in Exhibit 24. The figure compares a 20 MHz wide channel using a contiguous 2x20 MHz block of spectrum with a 20 MHz wide channel created by aggregating two non-contiguous 2x10 MHz blocks. It shows that CA reduces low-band capacity and lowers average user-experienced speed during busy hours of the day. Therefore sub-1 GHz CA is not will never be a substitute for making additional sub-1 GHz spectrum available.

Given the scarcity of sub-1 GHz spectrum, good practice in spectrum management would aim at allocating wider bands to operators rather than splitting all bands between operators. Additional sub-1 GHz spectrum would make this possible.

Exhibit 24: 2x20 MHz contiguous vs. two 2x10 MHz blocks

	2x20 MHz	2x10 + 2x10 MHz
Complexity	Single carrier	Needs intra-band CA
Channel utilisation	91.9%	86.7%
Physical layer signalling	6.3% overhead	Approx. 12% overhead
Physical layer configuration	A single 2x20 MHz carrier offers more flexibility than two 2x10 MHz carriers to configure sub-bands within the carrier	
Carrier activation/ deactivation delay	2 ms	10 ms
BS implementation	Requires one radio unit only	May need two radio units
UL support	No CA required in the UL	Uplink CA may not be supported by all UEs
UE consumption		30 mA additional power consumption for the second CC (50–90% RF power increase over the non-CA case)

Source: ECC. (October 2018). *ECC Report 287: Guidance on defragmentation of the frequency band 3400–3800 MHz*, p. 44; Coleago Consulting.

12 Options for additional sub-1 GHz spectrum for IMT

Additional sub-1 GHz spectrum can be found in the range below the 700 MHz bands, and in North America below the 600 MHz band. However, depending on the country, the frequency range may be used for broadcasting. In Region 3, the 470-694 MHz frequency band is allocated to the broadcasting service and mobile service on a co-primary basis. The US,Canada, Mexico and several other countries in Region 2, also identified this band for IMT through footnotes 5.295 and 5.308A. In Region 1 the spectrum has a primary identification for broadcasting, but momentum is building for mobile use.

The use of digital terrestrial broadcast TV (DTT) varies considerably from country to country, but is declining in all countries. This is due, in part, to the changing nature of TV from a linear broadcast service to an on-demand streaming service.

The use of digital terrestrial broadcast TV (DTT) varies considerably from country to country but is in overall decline. This is due, in part, to the changing nature of TV from a linear broadcast service to an on-demand streaming service. Broadcasters now offer a converged user experience. For example, viewers who join a TV show mid-programme are offered the opportunity to watch the TV show from the beginning at the click of a button. TV service delivery is changing from broadcast to broadband delivery.

There is considerable momentum for making spectrum below 700 MHz available for IMT, with several countries already making 600 MHz available for mobile or planning to do so.

There is considerable momentum for making spectrum below 700 MHz available for IMT, with several countries already making 600 MHz available for mobile or planning to do so:

- 600 MHz (Band n71) spectrum licences have been awarded in Canada and the US and 5G has been deployed in the band, while countries including Argentina, Colombia, Guatemala, Mexico, Uruguay, Saudi Arabia and Hong Kong have made progress in making the 600 MHz band available to mobile operators.
- In Region 3,AWG has begunb development of a 2x40 MHz band plan which overlaps with Band n71. A 3GPP specification is expected by the end of 2022
- Indian regulator TRAI recently unveiled plans in a 2021 consultation document,[23] stating that it was possible to dedicate the entirety of the frequency range 526–698 MHz for IMT/5G.

[23] TRAI. (30 November 2021). Consultation Paper on Auction of Spectrum in frequency bands identified for IMT/5G, p. 22

Appendices

Appendix A: 3GPP Rel. 17 NR Sub-1 GHz bands

The bands shown are from the published version of Release 17 of the respective 3GPP technical standard (TS 38.101) for the 5G NR standard. The NR bands are defined with the prefix “n”. When the NR band overlaps with the 4G LTE band, they share the same band number.

Exhibit 25: Sub-1 GHz NR bands

Band	Duplex mode	MHz	Common name	Subset of band	Uplink (MHz)	Downlink (MHz)	Channel bandwidths (MHz)
n71	FDD	600	Digital Dividend (US)		663–698	617–652	5, 10, 15, 20, 35
n12	FDD	700	Lower SMH	n85	699–716	729–746	5, 10, 15
n13	FDD	700	Upper SMH		777–787	746–756	5, 10
n14	FDD	700	Upper SMH		788–798	758–768	5, 10
n28	FDD	700	APT		703–748	758–803	5, 10, 15, 20, 30
n29	SDL	700	Lower SMH		N/A	717–728	5, 10
n67	SDL	700	EU 700		N/A	738–758	5, 10, 15, 20
n83	SUL	700	APT		703–748	N/A	5, 10, 15, 20, 30
n85	FDD	700	Extended Lower SMH		698–716	728–746	5, 10, 15
n20	FDD	800	Digital Dividend (EU)		832–862	791– 821	5, 10, 15, 20
n82	SUL	800	Digital Dividend (EU)		832–862	N/A	5, 10, 15, 20
n26	FDD	850	Extended CLR		81– 849	859–894	5, 10, 15, 20
n5	FDD	850	CLR	n26	824–849	869–894	5, 10, 15, 20, 25
n18	FDD	850	Lower 800 (Japan)	n26	815–830	860–875	5, 10, 15
n89	SUL	850	CLR		824–849	N/A	5, 10, 15, 20
n8	FDD	900	Extended GSM		880–915	925–960	5, 10, 15, 20, 35
n81	SUL	900	Extended GSM		880–915	N/A	5, 10, 15, 20

Source: 3GPP Release 17

Frequency division duplexing (FDD); time division duplexing (TDD); FDD supplemental downlink (SDL); FDD supplemental uplink (SUL)

Appendix B: **Frequency range**

Exhibit 26: Frequency bands in the 470–890 MHz range in the ITU Radio Regulations

<table>
<tr><th colspan="3">Allocation to services</th></tr>
<tr><th>Region 1</th><th>Region 2</th><th>Region 3</th></tr>
<tr><td rowspan="6">470-694
BROADCASTING

5.149 5.291A 5.294 5.296 5.300 5.304 5.306 5.312</td><td>470-512
BROADCASTING
Fixed
Mobile
5.292 5.293 5.295</td><td rowspan="2">470-585
FIXED
MOBILE 5.296A
BROADCASTING

5.291 5.298</td></tr>
<tr><td rowspan="2">512-608
BROADCASTING
5.295 5.297</td></tr>
<tr><td rowspan="2">585-610
FIXED
MOBILE 5.296A
BROADCASTING
RADIONAVIGATION
5.149 5.305 5.306 5.307</td></tr>
<tr><td rowspan="2">608-614
RADIO ASTRONOMY
Mobile-satellite except aeronautical mobile-satellite (Earth-to-space)</td></tr>
<tr><td rowspan="7">610-890
FIXED
MOBILE 5.296A 5.313A 5.317A
BROADCASTING

5.149 5.305 5.306 5.307 5.320</td></tr>
<tr><td rowspan="2">614-698
BROADCASTING
Fixed
Mobile
5.293 5.308 5.308A 5.309</td></tr>
<tr><td rowspan="2">694-790
MOBILE except aeronautical mobile 5.312A 5.317A
BROADCASTING
5.300 5.312</td></tr>
<tr><td rowspan="2">698-806
MOBILE 5.317A
BROADCASTING
Fixed

5.293 5.309</td></tr>
<tr><td rowspan="2">790-862
FIXED
MOBILE except aeronautical mobile 5.316B 5.317A
BROADCASTING
5.312 5.319</td></tr>
<tr><td rowspan="2">806-890
FIXED
MOBILE 5.317A
BROADCASTING

5.317 5.318</td></tr>
<tr><td>862-890
FIXED
MOBILE except aeronautical mobile 5.317A
BROADCASTING 5.322

5.319 5.323</td></tr>
</table>

Source: ITU Radio Regulations

Appendix C: Sub-1 GHz and mid-bands spectrum and capacity

Exhibit 27: Sub-1 GHz vs. mid-bands spectrum and DL capacity

Band	MHz in band	of which used for DL (MHz)	MIMO configu-ration	bits/s/Hz - DL	DL capacity per sector (Mbit/s)
Sub-1 GHz FDD	190	95	4x4	1.8	171
Sub-1 GHz TDD	20	20	4x4	1.8	36
Lower Mid Band FDD	410	205	32x32	2.2	451
Lower Mid Band TDD	80	60	32x32	2.2	132
Lower Mid Band SDL	90	90	32x32	2.2	198
Upper Mid Band TDD	400	300	64x64	6.0	1,800
Total sub-1GHz	210	115			207
Total mid-bands	980	655			2,581
Share of sub-1GHz	18%	15%			7%
Share of mid-bands	82%	85%			93%

Note: Depending on the country and region these value may vary slightly but this represents a typical situation. We assume that all sub-1 GHz and all mid-bands spectrum is deployed on every site.In dense urban areas small cells may not have sub-1 GHz spectrum while in rural areas there may be some sites which only have sub-1 GHz spectrum.

Source: Coleago

