Mobile Networks, Spectrum and Public Policy Outlook to 2030

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Glossary

Scope and purpose of this report

This document is addressed at mobile operators and telecoms regulators in developed as well as emerging markets.

This presentation is based on the Coleago report 'Mobile Services, Spectrum and Network Evolution to 2025' (March 2021), updated to align with the latest developments as well as with market projections to 2030

Aimed at **telecoms regulators** and **mobile operators,** it provides a review for of key global developments, insights, trends, and best international practices to inform future spectrum policy and management as well as operator strategies.

Key areas of focus:

- We consider the evolution of mobile services and applications, of the adoption and consumption of mobile data services, and of mobile network capacity requirements – projected to 2030, on a global and regional basis (see Chapter 1)
  - Specifically, we explore the evolution of underlying demand, mobile network constraints (coverage and capacity gaps) and actual mobile data consumption, using a Traffic Development Index (TDI) approach (see next slide)
- We consider the economic implications of the changing mobile landscape, both from a societal and an industry perspective
- Taking account of the evolution of mobile networks and technology over the 2023-2030 period, we estimate spectrum demand for a sample of developed and emerging markets (from a societal perspective – see Chapter 5)
- Separately, we discuss the business case for spectrum acquisition from an operator perspective (see Chapter 7)
- Finally, we explore the implications for spectrum management and pricing, focusing on the sustainability of the industry and of the socio-economic gains delivered by mobile communications (see Part III)

This document was commissioned and funded by Huawei. Except where otherwise stated, the views expressed are those of the authors, or of quoted third-party sources, and do not necessarily reflect Huawei's corporate position.

Disclaimer:
The demand forecasts presented in this report are based on quoted secondary (i.e. external) research rather than Coleago's own analysis. Other than our geometric extrapolations and 'best-fit' interpolations of the data, we concentrate on what would need to occur for these projections to materialise, and on their implications for operators and for public policy development.

Traffic Development Index (TDI) methodology

TDI analysis reveals the impact of network constraints on consumption, linking demand with actual traffic.

We have applied the TDI approach to the global mobile traffic forecast within this report – a key objective of this approach is to reveal the extent to which network coverage gaps and congestion suppress mobile consumption

TDI approach[1]:

Mobile Broadband (MBB) traffic demand index + Fixed Wireless Access (FWA) traffic demand index + 'New Services' (IoT, etc.) traffic demand index

Combined Unconstrained Demand Evolution

×

Network Constraints Factor

= Actual evolution of traffic on networks (Index)

'Unconstrained demand'
Traffic that would arise if mobile network coverage were 100% and there was no congestion

Impact of network constraints

Application of TDI approach in this report:

Our starting point for the traffic forecasts presented in this report are Ericsson's global projections to 2029[2]. These reflect traffic actually carried on mobile networks rather than unconstrained demand.

Separately, we estimate the extent to which network constraints suppress demand, by assessing:

- Current and projected terrestrial mobile coverage
- Current network capacity constraints (congestion) and their assumed evolution, based on data collected by Huawei across a range of markets

From the above, we estimate the evolution of unconstrained mobile data demand. Thus, starting from 'net' (actual) traffic, we work backwards to 'gross' (unconstrained) traffic across the three main categories (MBB, FWA and 'new services'), to obtain a complete picture.

This allows us to gauge the extent to which potential demand is unmet, which has economic consequences for operators as well as social and economic consequences for the wider public

[1] As we apply it, we set the combined (unconstrained) Traffic Demand Index to 100 for 2023. The 2023 indices for the individual components (MBB, FWA, etc) are this set to add up to 100. After multiplying unconstrained demand by the Network Suppression Factor, we renormalise the actual traffic index to obtain 2023 = 100.. [2] Ericsson Mobility Report, November 2023

TDI in relation to demand for capacity and spectrum

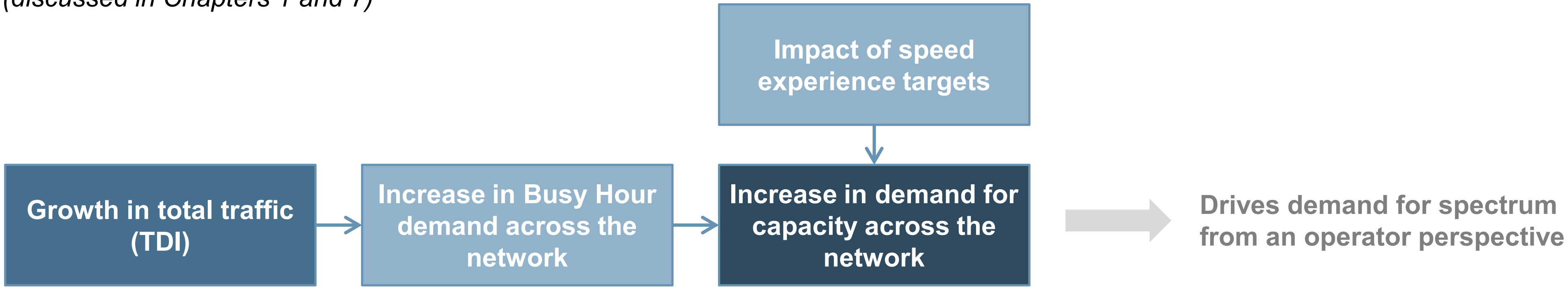
Spectrum need from a societal perspective differs from spectrum value for operators.

Spectrum demand from an operator perspective relates to willingness to pay for it, taking commercial trade-offs into account

- TDI is a key driver, but it is not the only one: data speed experience targets, which bear on customer satisfaction levels (hence on operators' competitive position), also have a significant impact
- Globally, we project a 4x average increase in data demand between 2023 and 2030, and based on our own modelling, we estimate that a consistent 100Mbps speed experience roughly doubles the capacity need (see Chapter 1) – implying **8x** capacity uplift is required to meet demand at such speeds

Capacity need and spectrum demand for operators[1]:

(discussed in Chapters 1 and 7)



From a societal perspective, total spectrum need relates to the bandwidth required by the mobile industry to carry traffic where it is most concentrated, such as in dense urban settings at the busiest times

- This is a function of maximum traffic density (Mbps per square km) rather than of country-wide mobile data volumes (TDI)
- We estimate social spectrum need on the basis of 'activity factors', which reflect the level of concurrent demand for 100Mbps connections within a given area

(social spectrum demand is discussed in Chapter 5)

[1] On a 'best effort' basis (i.e. without any specific speed experience targets), growth in capacity-need is driven solely by growth in data traffic (assuming the same busy-hour traffic profile). On a global basis, this is projected to grow by 4x multiple between 2023 and 2030 (see Ch.1). Moving from best-effort to a speed experience target of 100Mbps with 99% probability imposes a further 2x increase in capacity need. .

Delivering optimal outcomes for your country: traffic, spectrum and societal benefit

The purpose of 4G and 5G networks is to enable mobile data traffic.

The amount of traffic transmitted by networks is a proxy for socio-economic value.

Maximising socio-economic value should be the overriding objective of spectrum policy and policies that enable network investment.

Key take-aways for policymakers from this report may be summarised as follows

First principles

The purpose of 4G & 5G networks
Transport data traffic

→

Socio-economic value
The amount of data traffic per capita is a proxy for socio-economic value delivered by 4G & 5G networks

→

Policy implications
Policies which maximise the amount of traffic also maximise socio-economic value

Building blocks to deliver optimum outcomes for your country

Traffic Development Index

- Minimise the network suppression factor
- Increase capacity in urban areas by maximising mid band spectrum availability including C-Band and 6 GHz
- Foster coverage of populated areas by assigning all low band spectrum including 600 MHz (n71/n105) and 1500 MHz (n75)

Maximise the value of spectrum

- Unused spectrum generates no value
- Spectrum which is used reduces producer costs and increases the consumer surplus
- Make all spectrum identified for IMT available as early as possible and as cheaply as possible

Ensure that operators have a business case for network investment

- Sustainable spectrum pricing
- Measures to reduce deployment costs
- Infrastructure sharing
- Deployment of IMT spectrum on LEO satellite for lower cost rural coverage

Minimise consumer costs

- Make all IMT spectrum available because it reduces network costs leading to lower prices
- Allocate at least per operator 100 MHz in mid bands and 2 x 15 / 2 x 20 MHz in low bands
- Make public infrastructure available for site deployment

Executive Summary

Key findings and calls to action

Dramatic changes in mobile comms are set to continue beyond 2030

The fast-changing mobile landscape brings both risks and opportunities.

Operators and policymakers need to respond positively to these challenges to ensure favourable outcomes.

See Chapter 1 for details (Ch.2 for Evolving Architectures)

Megatrends from 2023 to 2030 include the emergence of hyperconnectivity - fully immersive digital experiences with the creation of the Metaverse, and the relentless advance of AI-powered automation

Commercial 6G by 2030

- Bigger leap in efficiency and performance from 5G to 6G than from 4G to 5G
- Key to innovation & differentiation with 5G Advanced as first step

Hyperconnectivity

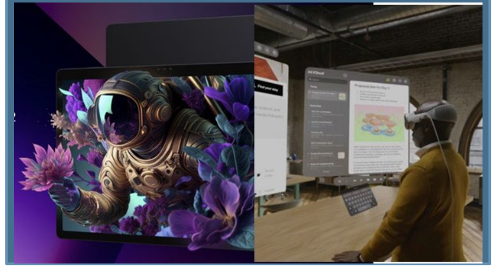
- LEO revolution: Satellite D2D
- Truly global coverage for billions of smartphones, from ~33% of dry landmass and ~10% of Earth's surface served by terrestrial mobile

Industry & Consumer Metaverse

- Seamless merger of physical and digital realities
- $766 billion market by 2030, with a key role for mobile networks

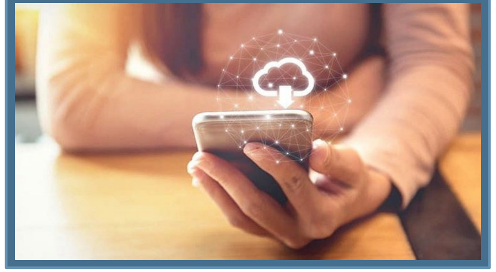
Naked-eye 3D & Mixed Reality

- Potential mass-market appeal as device prices fall by 2030
- Significant drivers of potential future demand for bandwidth, including mobile and FWA



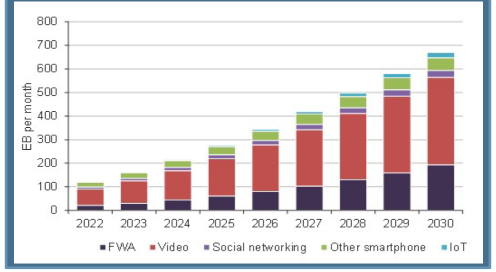
Mobile Cloud applications

- Harness remote processing power
- Higher scalability, reduced costs, longer device battery life, cross-platform inter-operability and wider market reach



4x global mobile traffic by 2030

- #1 driver: smartphone traffic, with by increased video, gaming, MR and 3D usage at higher bit rates
- #2 driver: Fixed Wireless Access (FWA)

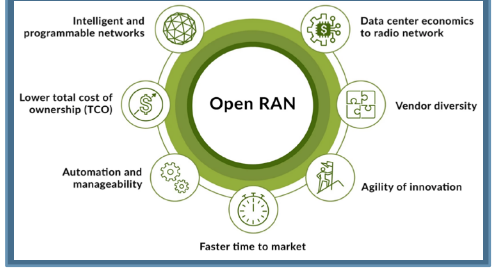


Emerging segments

- Doubling of cellular IoT connections
- Mobile Fintech: over 10% of some operators' service revenues
- Private Mobile Networks: 10% contribution to revenues by 2030

Evolving architectures

- Open RAN will promote greater vendor diversity, inter-operability and agility = superior performance outcomes and lower costs
- Small cells rising in prominence



Note: image and source attributions are provided within the main body of this report.

Projected 4x growth in mobile traffic between 2023 and 2030

Existing and future network constraints must be addressed to achieve the full potential of mobile communications and maintain competitive advantage.

Policymakers have a major role to play in helping the industry to address these constraints (see Chapter 3 and Part III).

See Chapter 1 for additional details and explanations, and Appendix A for detailed calculations

When analysing of the evolution of mobile traffic, it may be helpful to isolate the influence of network coverage and capacity constraints on consumption – using the following 'Traffic Development Index' (TDI) approach[1]

Unconstrained global demand (2023 → 2030):

Traffic index = normalised, blended adoption x usage
Individual indices such as to add up to 100 in 2023

Note: only IoT is directly quantified in the traffic forecasts

Mobile Broadband (MBB) index
Total SIM penetration: 96% → 102%[1]
5G SIM penetration : 38% → 76%
4G AUPU: 21 → 33 GB/SIM
5G AUPU: 26 → 77 GB/SIM
Traffic demand index: 80 → 254

MBB: 80% of total demand in 2023
2030 index 254 = 80 x 3.1
3.1x blended demand growth to 2030

+

Fixed Wireless Access (FWA) index
Total SIM penetration: 1.8% → 4.5%
5G SIM penetration: 0.9% → 4.3%
4G AUPU: 255 → 284 GB/SIM
5G AUPU: 315 → 647 GB/SIM
Traffic demand index: 19 → 108

FWA = 19% of total demand in 2023
2030 index 108 = 19 x 5.7
5.7x blended demand growth to 2030

+

'New Services' index
IoT SIM penetration: 38% → 66%
IoT SIM AUPU: 0.84 → 4.2 GB/SIM
(note: tethered wearable IoT traffic is reflected in MBB)
Traffic demand index: 1 → 11

IoT = 1% of total demand in 2023
11x demand growth to 2030
2030 index 11 = 1 x 11

= Unconstrained total traffic demand index: 80+19+1 = 100 → 373 (3.7x) *Index: 2023 = 100*

×

Constrained global demand (2023 → 2030):

Note: coverage suppression will be mitigated by Satellite D2D, however our forecasts relate to terrestrial mobile traffic (coverage from 90% to 95% 2030)

Network Suppression Factor: 0.74 → 0.81 *Factor: 1.0 = no suppression*
[= Coverage Suppression Factor: 0.87 → 0.91 (net impact on traffic due to suppressed 4G and 5G adoption)
× Capacity Suppression Factor: 0.85 → 0.89 (implies 15% traffic lost to congestion in 2023, 11% in 2030)[2]]

Renormalised such that 2023 index = 100

Resulting traffic index (renormalised): 100 → 412 (4.1x) *Index: 2023 = 100*

- 55% of total network traffic growth is due to increased smartphone video traffic (which is itself driven mainly by higher resolutions) while FWA accounts for 32% of total growth – ***both are enabled by 5G coverage growth from 49% of population to 87% in 2030***
- 3D, Mixed Reality and Gaming included in Video category rather than 'New Services' to align with our forecast data sources (note: 3D, MR and Gaming are also important future drivers of traffic per FWA connection) –also, tethered wearable IoT is reflected in MBB
- New Services include Private Networks (wholesale capacity provision rather than mobile traffic) and Mobile Cloud apps (not quantified)

[1] This approach considers unconstrained demand evolution, overlaying coverage and capacity constraints to obtain actual consumption. We assume for simplicity that coverage only affects adoption (linearly) while congestion only affects traffic per SIM – in practice, there may be combined effects.
[2] 2023 figures based on Huawei data. Projected 2030 figure reflects assumption that suppression rates will halve linearly over 10 years.

From traffic to demand for capacity

A bit of high-speed data is more costly to produce than a slow ('best effort'[1]) bit.

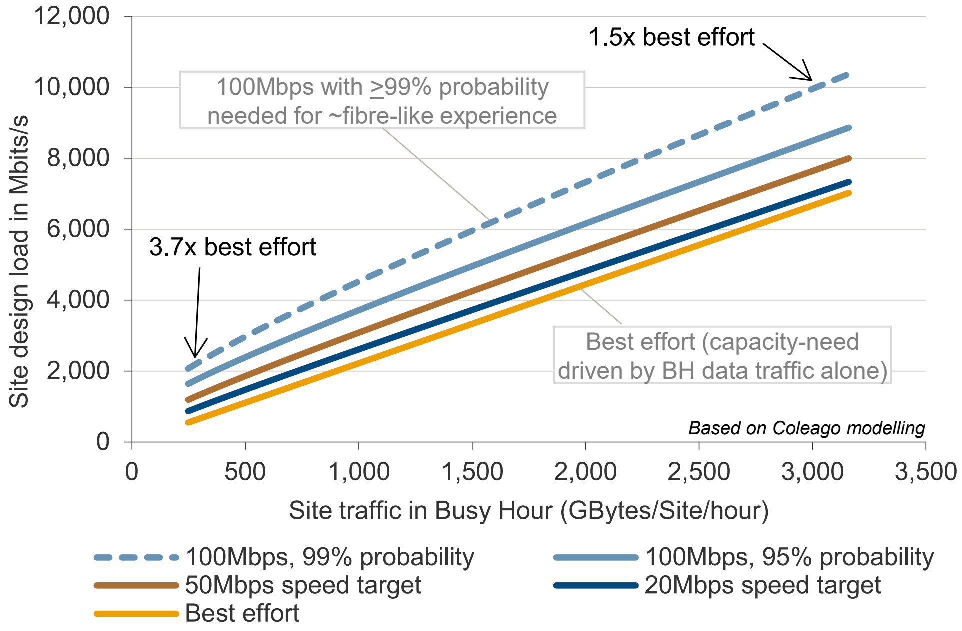
A consistent 100Mbps speed experience target would roughly double average network capacity need.

See Chapter 1 for additional details and explanations

The ITU IMT-2000 (5G performance) requirements specify a 100Mbps ('fibre-like') user-speed experience

- This reflects customer needs for higher data speeds to deliver an adequate broadband experience
- But a 'fast bit' of mobile data is more expensive to deliver than a 'slow bit': it requires greater network capacity
- Illustration: 2x as much capacity would be needed to deliver 100MB each to two users in the same second than one second apart
- 100Mbps speeds need to be delivered *at least* 99% of the time to start approximating fibre-like consistency

Impact of minimum data-speed targets on capacity requirements:



Due to statistical effects[2], the % impact of speed targets on capacity-need is lower where traffic intensity is higher

Relative to 'best effort'[1], we estimate that a **100Mbps** speed experience target delivered with **99% probability** drives a:

- **~3.7x** increase in capacity need where traffic intensity is low
- **~1.5x** increase in capacity need in the busiest areas (such as in dense urban locations)
- **~2x** increase in average capacity need across the entire network

Capacity need	Global	DM*	EM*
GB/capita/month 2023 → 2030	20→80	40→134	4→21
Total network traffic 2030 vs 2030	4.1x	3.4x	7.0x
Average capacity-need across the network (2030 vs 2023):			
Best Effort (traffic impact alone[3])	**4.1x**	3.4x	7.0x
Plus 100Mbps target (99% prob.)	**8.2x**	6.8x	14.1x
Capacity-need in busier parts of the network (e.g. dense urban):			
Best Effort (traffic impact alone)	4.1x	3.4x	7.0x
Plus 100Mbps target (99% prob.)	**6.1x**	5.1x	10.5x

* Western Europe (lowest TDI growth) is taken as example for Developed Markets (DM), sub-Saharan Africa (highest DTI growth) for Emerging Markets (EM). Note: while we show the impact of 100Mbps speed targets, we recognise that these are less likely to be delivered in EM by 2030
** Taking population growth into account

To meet the 100Mbps speed target, ~**8x** more capacity would be needed globally – with ~**6x** needed in busy areas

- For DM ~**5x** more will be needed in busy areas by 2030
- For EM ~**10x** more in busy areas, *if* the target is met by 2030

[1] *'Best effort' data provision means delivery of a given quantity of GBytes during the busy hour without regard to data-speed experience requirements.*
[2] *To illustrate: an increase from 2 to 3 concurrent users in a cell imposes a far greater % increase in capacity-need (+50%) than from 10 to 11 (+10%).*
[3] *While there may be spare capacity in some areas, our modelling suggests that % increases in deployed capacity align broadly with % increases in traffic.*

Addressing network-capacity constraints

Significant macro densification may not be feasible in dense urban areas. New mid band spectrum will be needed to meet future traffic demand.

See Chapter 2 and 3 for additional details

Direct-to-smartphone satellite may bridge the coverage gap, but far more capacity is needed, especially in dense urban areas

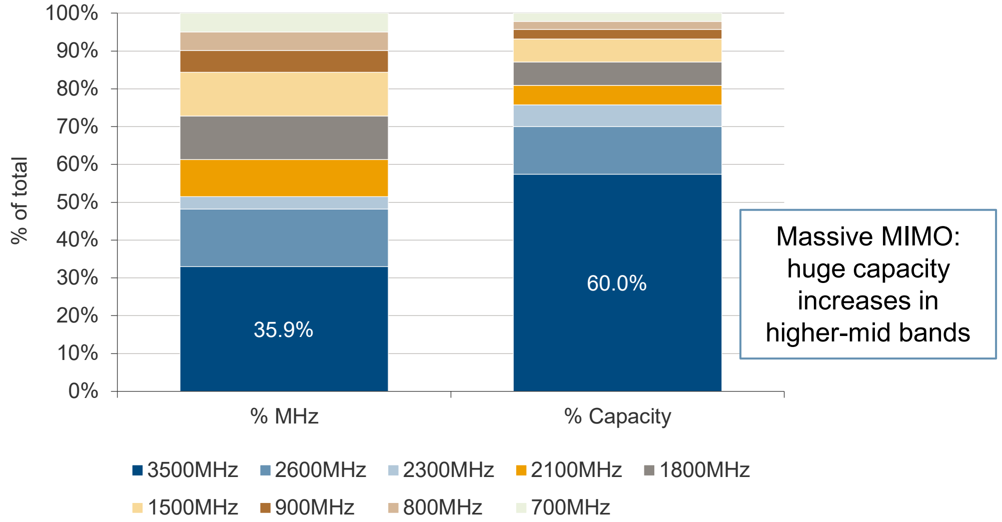
- Additional mid band spectrum remains the main source of extra capacity, especially in dense urban areas

Illustrative route to capacity expansion (dense urban)	Capacity
+100 MHz to all MNOs (e.g. 2.3GHz), 4T MIMO	+8%
+200 MHz to all MNOs (e.g. 3.6-3.8GHz), 32T MIMO	+42%
+700 MHz to all MNOs (e.g. U6G), 32T MIMO	+95%
Double MIMO order (to 64T MIMO in higher mid band)	+22%
35% extra offload to small cells and mmWave bands	+35%
Combined impact on capacity	**+5x**

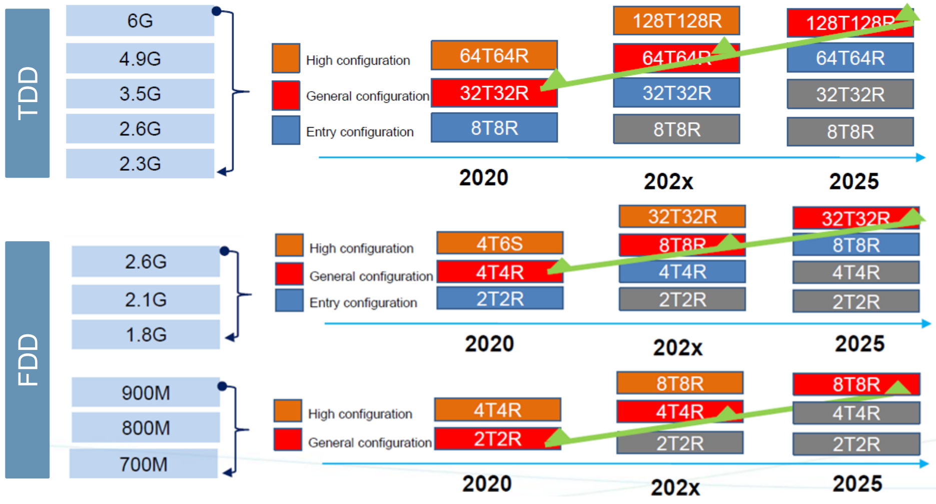
A 5x increase would be sufficient for most developed markets but more will be needed beyond 2030:

- Massive MIMO (see Ch.2) will help drive higher capacity per MHz: with 64T alone, 3.4-3.8GHz could account for 60% of capacity from frequencies below 4GHz
  - Higher order MIMO is available: Huawei announced the launch of 128T Meta Massive MIMO at MWC24[2]
- Greater small cell and mmWave deployment will also help
- For EM: initial spectrum allocations are typically more limited than in DM, giving a greater potential uplift from extra mid band
  - The scope for dense-urban capacity expansion from site densification is also likely greater in EM

Relative bandwidth and capacity by band (with MIMO 64T at 3.5GHz)



Huawei MIMO evolution roadmap



TDD: Time Division Duplex; FDD: frequency Division Duplex (see Chapter 2)

[1] *Coleago estimate: up to 2x as much capacity may be needed to deliver 100Mbps with 99% probability versus 'best effort' traffic – a fast bit is more expensive to carry than a slow one.* [2] *21 February 2024: Huawei claims a doubling of spectral efficiency to 12+Gbps capacity, with +5dB coverage gain.* [3] *Higher-order MIMO is more restricted in lower bands due to larger antennas, limiting the MIMO uplift in these.*

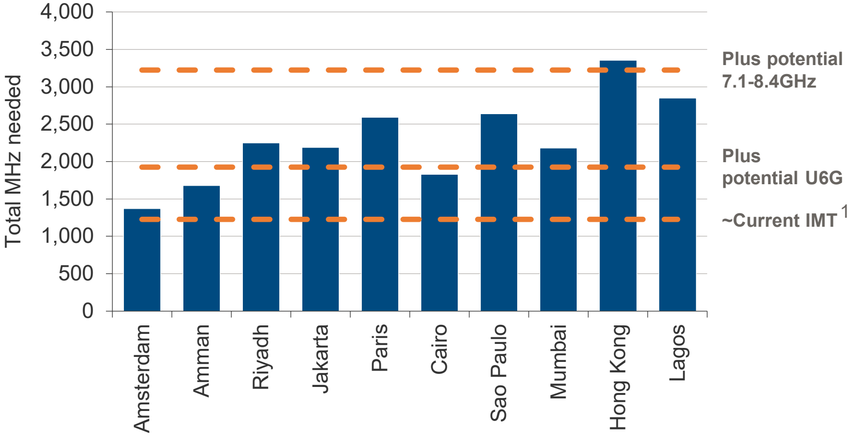
Spectrum need from a societal perspective

Bandwidth shortfalls caused by a failure to release sufficient IMT-designated spectrum could result in substantial socio-economic harm.

See Chapters 4 and 5 for additional details

Spectrum need to meet the 5G speed experience requirements (100Mbps downlink plus 50Mbps uplink)

Central estimates (low+mid band MHz uplink+downlink):



1260-3690 MHz low and mid band needed to meet 5G data-speed requirements in cities with >8000 inhabitants per square km

- Max high-income countries: Hong Kong (upper-bound estimate = 3,690 MHz)
- Max upper middle income: Sao Paulo (upper-bound estimate = 2,640 MHz)
- Max lower middle income: Lagos (upper-bound estimate = 3,260 MHz)
- **Upper 6GHz** (U6G) plus additional spectrum in the **7.1-8.4GHz** range would be needed in all ITU regions to meet the needs in the densest cities[2]
- The above assumes significant traffic offloaded onto mmWave spectrum (**~3GHz** needed for above and for 10Mbps/sq.m area-capacity requirement[2])
- Additional mid band spectrum would allow for sustainable rural FWA

low band spectrum need (sub-1 GHz)

- low band most congested (10-20% share if traffic vs ~7% share of capacity) – more needed for (indoor) cell edge performance as traffic grows – yet sub-1 GHz spectrum is very scarce, and it is unlikely that supply in this category can be increased by more than 50%
- Future demand will likely exceed supply – releasing the maximum possible amount of 600 MHz for mobile by 2030 should be a high priority for policymakers, to avoid undue degradation in the (indoor) quality of mobile services in the mid-term

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
						

1 *Approximately 1225MHz currently available, whether allocated or not; includes 100 MHz at 2.3GH and varies across regions and countries.*
2 *U6G addressed in WRC-23 (see Ch.4 for additional details on status). The 7.1-8.4GHz range has been included in the agenda for WRC-27.*

Summary of key priorities 2023-2030

Making the best use of available technologies and spectrum should remain central to the plans of operators and policymakers alike.

With the right spectrum combination, 5G Advanced could deliver 5Gbps peak speeds - a cross mobile-generation step change in user experience[1].

See Chapter 3 for additional details

While market conditions may differ across emerging and developed markets, additional low and mid band spectrum is essential to meet the fast-growing needs of consumers and businesses in all mobile markets

- Sub-1 GHz bands remain the most congested and heavily utilised on a per MHz basis (see Chapter 5). More is needed to improve indoor and wide area network quality - this will have a disproportionate impact on user experience hence on competitive advantage
- Significantly more mid band spectrum is needed to meet the 3.4-7.0x traffic growth factor and to increase experienced data speed rates

Priorities in High-Income countries

Additional spectrum:

- A renewed focus on freeing up spectrum in the **600 MHz** band for mobile use is called for (see Ch. 4 and 5 for further discussion)
- Additional 3.3-4.3 GHz, and accelerate upper 6 GHz awards

Expanding 5G population coverage (especially in Europe):

- Europe (70%) significantly lags North America and China (95%)

Upgrading to 5G SA and 5G Advanced, higher MIMO order[2]:

- Operators need to harness the potential of technology, especially **5G Advanced**, to pursue additional revenue streams, strengthen their competitive position, and to drive operational efficiency
- Deploy higher order MIMO across bands to mitigate spectrum insufficiency – drive capacity per MHz and extend cell coverage
- Suitable operator paths to 5G Advanced include:
  - 3 TDD CA across wider 3.3-4.2GHz range with 2.3/2.6 GHz
  - 2 TDD CA, e.g. 3.4-3.6 with 2.3/2.6 GHz, plus mmWave
  - 2 TDD carriers 3.3-4.2 GHz plus 50 MHz FDD
  - TDD (e.g. 2.6 GHz) with FDD (e.g. 700 MHz) plus mmWave

Priorities in Emerging markets

Additional spectrum:

- Full **800 MHz** and **700 MHz** allocation
- **2.3 GHz**, **2.6 GHz** and full **3.4-3.8 GHz** to meet high data growth, improve data experience and enable FWA[2]

Expand MBB coverage[3]:

- The population coverage gap for MBB is generally far wider in emerging markets – reducing it will benefit society and allow operators to address latent demand

Technology neutrality

- Licences need to be technology neutral to allow operators to optimise the technology mix across their spectrum holdings

Spectrum pricing reforms:

- High spectrum costs drain operator capital, impeding investment
- In particular, these are excessive and need to be significantly reduced in Pakistan, Bangladesh and Indonesia (see Chapter 9)
- Payment methods should also be reformed, to allow licence fees to be spread more evenly during the licence term (see Ch.9)

[1] Huawei vision..
[2] See Chapter 2 for additional detail, including an introduction to 5G SA, 5G Advanced, MIMO, Carrier Aggregation (CA), and TDD vs FDD..
[3] Mobile will play a comparatively more important role in delivering broadband in emerging markets due to weaker fixed infrastructures.

The business case for spectrum and technology investment

Operators' focus should be on maintaining a competitive spectrum portfolio as well as on service capabilities, network efficiency and performance – and on reducing opex.

Technological obsolescence is never a viable option.

See Chapters 3 and 7 for additional details

Spectrum investment rationale

- Operators should invest in additional spectrum if its value exceeds its cost (i.e. spectrum price plus cost of deployment)
- Key value drivers include:
  - **Cost avoidance**: a given capacity-need is cheaper to meet by deploying spectrum than with network densification
  - If cannot 'build' out of congestion (due to a lack of suitable or affordable site options), extra spectrum may have a **market share impact** – driving potentially higher spectrum values
  - Extra spectrum may allow operators to address **new revenue streams** more effectively*

Technology investment rationale (e.g. 5G Advanced)

- Given competition, it is essential to keep up with the evolving needs and expectations of key customer groups, as well as to use every opportunity to drive operational efficiencies
- Key value drivers for 5G Advanced include:
  - Bringing AI into mobile networks to **boost capabilities** and efficiency is a logical step that mirrors developments in other industries
  - **Revenue upside:** new and improved services*, including smart production and productivity
  - **Opex upside (savings):** greater network energy efficiency, streamlined network management

Illustration: network-cost avoidance value of spectrum

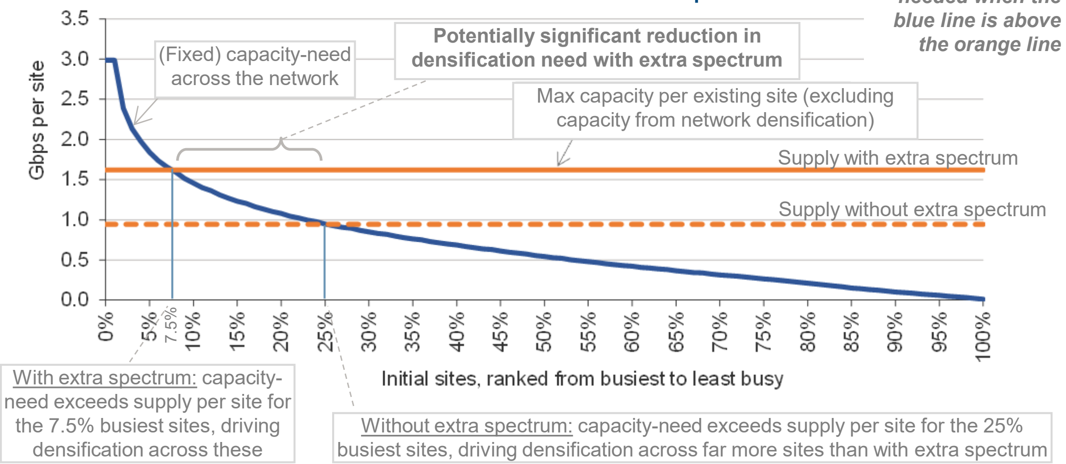
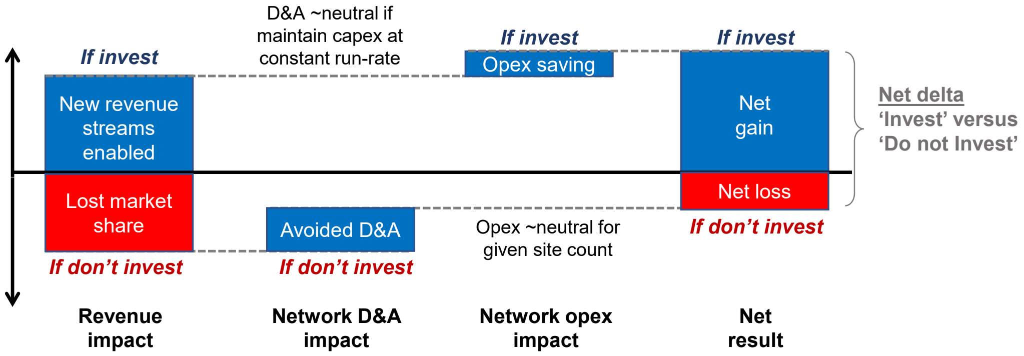


Illustration: case for mobile technology investment (not to scale)



D&A = Depreciation and Amortisation. If one doesn't invest (e.g. in 5G Advanced), one may lose revenues, but avoid extra D&A costs

*Invest to: (1) More effectively address **FWA**, **critical IoT** and **network-slicing based Private Mobile Networks**; (2) Enable **speed-based** and **quality-of-service based pricing**; (3) Better serve needs for **immersive and 3D applications** and **Mobile Cloud Computing**

Very high socio-economic impact of mobile

There are very few parts of society and of the economy that are not touched by mobile communications.

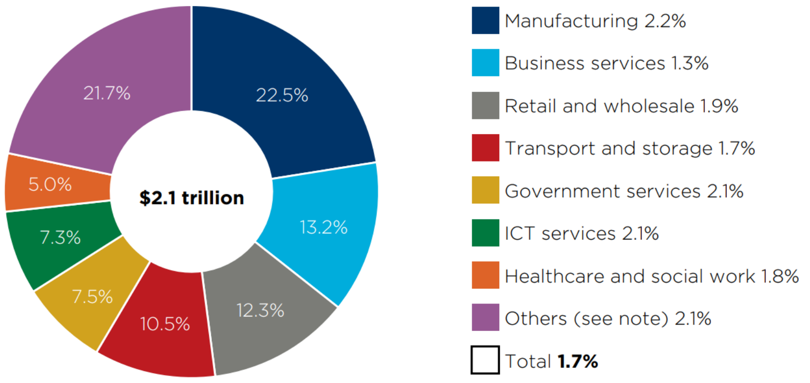
Mobile allows us to stay informed, drives the wheels of the economy, and keeps us entertained and safe.

See Chapter 8 for additional details

The mobile industry is a key industry with powerful externalities – policymakers need to treat it with care

Mobile externalities → **Very large *absolute* contribution to the economy** **plus to consumer welfare** → **Large *marginal* impact on economic development** **plus to consumer welfare**

Sectoral distribution of global productivity-enabled GDP gains from full 5G rollout in 2030



growth in sector economic output associated with 5G-enabled technologies.

Graphic courtesy of Oxford Economics

The current coverage gap (~13% globally) and capacity shortfall (~15%) are very costly

- 10% extra population coverage could thus raise GDP per capita by up to **1.5%** – a gain in the order of total mobile industry revenues (~1% GDP)!
- Eliminating network congestion could increase the total consumer surplus (CS) from mobile use by up to 18% (almost a fifth) – with average CS of **~8x** industry revenues (based on US data), eliminating congestion could drive extra social gains in the order of **1.6x** total current consumer spend on mobile

Economic development is highly sensitive to adoption and usage of mobile services

↓

Adoption and usage is sensitive to network coverage and capacity (investment) and to retail prices

↓

Mobile investment and retail prices are sensitive to the financial position of operators and their ROIC[2] prospects

↓

The financial position of operators and their ROIC prospects are heavily influenced by public policy

↓

Hence socio-economic development is highly sensitive to public policy towards mobile
(Especially spectrum pricing policy)

Extra spectrum is needed at reasonable prices to allow the capacity expansion needed for substantial increases in traffic and reductions in prices per GB – which would drive very high welfare gains and boost economic development

Sustainable spectrum pricing

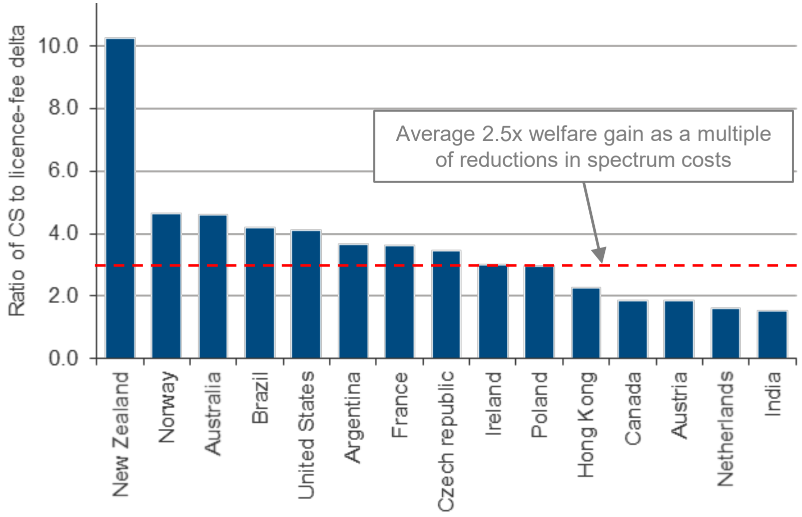
The State cannot extract vast amounts of capital from critical industries such as mobile without diminishing the productivity and welfare benefits that these industries generate for society.

It should seem obvious that high costs of spectrum will diminish the ability of operators to invest and to compete more aggressively on price.

See Chapter 9 for additional details

Provided that the market is competitive, higher spectrum prices are invariably worse for all stakeholders than lower price

- Evidence refutes the myth that lump-sum fees charged for licences do not bear on subsequent management decisions, because these are 'sunk costs'
- Quantitative research by NERA shows that welfare gains exceed reductions in licence fees by **2.5x** on average

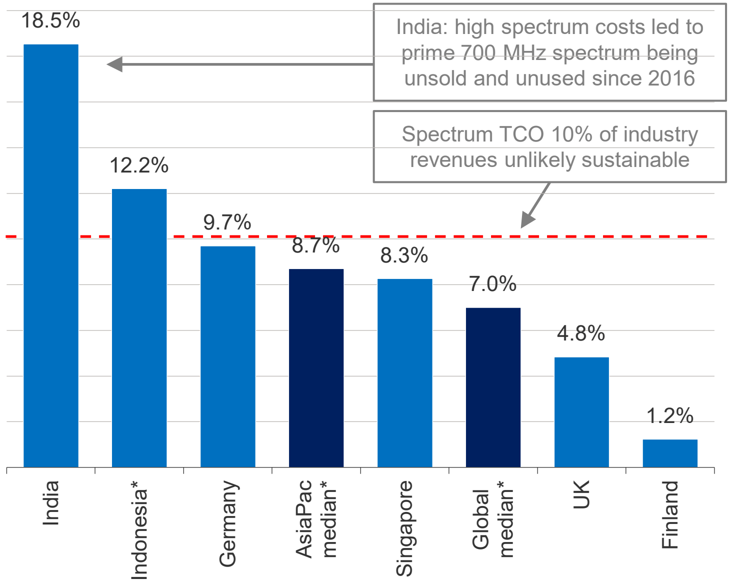


In 2009, total consumer surplus (welfare) in the US was **80x** higher than the $50bn in cumulative auction revenues that the FCC had collected until 2008 – and the net social gains were 240x higher.

Doubling spectrum fees would, if it reduced consumer surplus by just 0.5%, produce social costs in excess of benefits.

- 68% of the variation in mobile consumption intensity between countries is explained by differences in the annualised cost of spectrum
  - e.g. spectrum costs in Finland are just **1.2%** of revenues vs **9.7%** in Germany; as a result, Unlimited 5G costs **2.7x** more in Germany than in Finland
- Revenues *per MHz* are falling – costs *per MHz* need to fall too to be sustainable
- Unrealistic spectrum pricing impacts negatively on spectrum use, damaging 4-5G service provision a.o. in India, Pakistan, Bangladesh, Sri Lanka, Indonesia, Nepal, Ghana, Mexico and Brazil

Spectrum Price Index: spectrum TCO as % revenues[1]



* Based in GSMA analysis

Abundant spectrum priced reasonably best serves public interests:

- Promotes investment in coverage and capacity
- Enables deeper price erosion through competition
  - While allowing industry to earn its cost of capital
  - Thus, promoting sustainability of competition
- As a rule of thumb, if the aggregate spectrum TCO of all spectrum holdings exceed 10% of combined revenues, substantial damage to public interests may ensue

[1] *TCO: Total Cost of Ownership, on an annualised basis.*

International best practices – overview

Best practices imply evidence-based policies designed to improve mobile market outcomes for consumers and society.

With so much at stake, it is important to pursue policies that promote investment, innovation and competition.

Regulatory certainty	• Investors need long-term certainty – a stable policy landscape incentivises network investment • Perpetual or longer duration spectrum licences foster investment (European Commission view: at least 20 years; FCC: perpetual licences; Ofcom UK: perpetual licences with annual fees after initial term)
Moderate licence fees	• Avoid harm to investment and retail prices by driving up costs of key industry inputs • Coverage commitments in exchange for lower spectrum fees is better than fee maximisation • Phasing of licence payments is generally good policy, avoiding the need for operators to raise extra capital
Technology neutrality	• Technology neutral licences are now the norm in advanced economies • Competition incentivises operators to pursue efficient technology strategies • Lack of technology neutrality may also dissuade investment and innovation
Spectrum packaging	• Regulators should favour larger, contiguous holdings across fewer bands (wide band allocation) • Regulators should avoid split assignments within any given band – these are inefficient from both a performance and cost perspective, and future defragmentation may lead to equipment write-offs
Timing of awards	• Regulators should seek to accelerate the clearing of mobile-designated spectrum from legacy users and release the usage-rights to operators as quickly as possible (i.e. as soon as it is available, but not before) • Delays in spectrum awards constrain supply and consumption, leading to foregone social gains
Spectrum trading	• Regulators should promote spectrum trading (subject to competition safeguards) • While an operator may be the most efficient spectrum user at a given time, a rival might make better use of resources (and value these more highly) at a later point – trading could thus improve overall efficiency
Leverage public assets and support rural broadband	• Streamlining planning processes and making public real-estate assets (buildings and street furniture) readily available for mobile network deployment will serve the interests of local businesses and consumers • Subsidies for rural broadband development help overcome economic barriers and promote digital inclusion

Part I – Mobile Market and Technology Trends

Key drivers of spectrum demand to 2030

Chapter 1 Mobile market trends

Chapter 2 Networks and technology

Chapter 3 Implications for stakeholders

Part I

1

Mobile market trends

What will the world look like in 2030?

What will the world look like in 2030?

Megatrends from 2023 to 2030 include the emergence of hyperconnectivity, fully immersive digital experiences with the creation of the Metaverse, and the relentless advance of AI-powered automation.

The first live commercial deployments of 6G services will appear

- Emphasis will shift from Connected People and Things to Connected Intelligence
- Tbps-level peak data-rates, sub-millisecond latency, hypermobility (at over 1000Km/hr), 2-3x higher spectral efficiencies, and 10-100x higher network energy efficiency
- Meanwhile, 5G will continue to evolve, focused on 5G advanced, providing a stepping-stone to 6G

Hyperconnectivity: fading boundaries between networks

- Seamless access to terrestrial mobile, satellite and WiFi connectivity
- Low Earth orbit satellites will function as 'base stations in the sky', delivering truly global coverage and effectively wiping out the rural (as well as maritime) coverage divide
- The network of networks will connect billions of sensors as well as land and air-bound drones and robots, each with native AI – yielding a distributed, self-organising neural network underpinning the emerging Metaverse

Seamless merger of physical and digital realities

- Growing momentum in key Metaverse segments, generating a $766 billion market in 2030[1]
- Industry: simulated processed and physical assets ('digital twins'), enabling real world problem solving and optimisation across industry and manufacturing (56% of total)
- Immersive business collaboration with productivity tools and virtual workspaces (28%)
- Consumer: digital worlds and immersive spaces for shopping, gaming, socialising, and entertainment (16% of total Metaverse revenues)

Images courtesy of Huawei, x2n.com, and Style Magazine (scmp.com)

[1] *Projected market size from Persistence Market Research. Split of value by segment sourced from MIT Technology Review Insights, based on data from VentureBeat and ABI Research, 2022*

Global mobile traffic will rise to 4x the 2023 level

While traffic growth rates are slowing, they will remain within double-digits % until the end of the decade.

Image courtesy of TheConversation.com

Average mobile traffic per capita will grow from 20GB per month in 2023 to 80GB in 2030[1]

- Albeit the rate of growth will fall from 36% in 2023 to 15% in 2030 (22% CAGR 2023-2030)
- Global 5G will account for 83% of traffic in 2030, with legacy traffic (4G and other) peaking in 2027
- Video consumption will continue to dominate, increasing from 73% of smartphone traffic to 82% in 2030 – accounting for 55% of total mobile traffic growth 2023-2030
- Fixed Wireless Access (FWA) will contribute 29% of total traffic, up from 19% in 2023

Forecast summary (actual rather than 'unconstrained'):

Growth enabler: 2023-2030 population coverage rising from 90% to 95%+ for 4G and from 49% to 87% for 5G

Mobile Broadband (MBB)		Fixed Wireless Access (FWA)		'New Services'
Smartphone data demand: 2023 index: 80 (out of 100) 2030 index: 280 Smartphone adoption +17%, Usage per smartphone +237%	+	**FWA data demand:** 2023 index: 19 (out of 100) 2030 index: 119 FWA adoption +160%, Usage per FWA connection +130%	+	**IoT data demand[2]:** 2023 index: 1 (out of 100) 2030 index: 14 Other new services such as Mobile Cloud Applications and Private Networks are not explicitly reflected within these traffic indices[3]

Total data demand:
2023 index: 100 = 80 + 19 + 1
2030 index: 412 = 280 + 119 + 14

Starting with a total mobile data traffic index of 100 in 2023, a total of 412 in 2030 implies a 4.12x multiple. This assumes that demand is not unduly constrained by a future lack of network capacity (which would impair the typical user data experience).

Growth prerequisite: 4x global capacity growth factor to carry 4x data, doubled again for 100Mbps user-speed experience[4]

[1] Based on our geometric extrapolation of Ericsson forecasts to 2029. The 4x traffic multiple takes population growth into account. [2] IoT may be severely understated in external projections, with tethered wearable IoT traffic reflected in MBB. [3] Private networks involve wholesale capacity. The impact of Mobile Cloud apps on mobile traffic has not been quantified but may be significant. [4] ITU IMT-2020 defined requirement..

Over half of the growth in mobile data will come from smartphone video

Together, smartphone video and FWA account for 87% of the total projected growth in data traffic between 2023 and 2030.

#1 Driver: smartphone video (including gaming, 3D and XR)
(55% of total traffic growth)

Image courtesy of FreePik.com

- Increased smartphone penetration (especially 5G) and increased video streaming per smartphone, enabled by improved network quality and larger/unlimited data plans
- Increased resolution of video streaming and gaming, driving higher data consumption per hour of use (see next slide)
- Future mass adoption of AR, VR and MR on mobile[2]

63% of YouTube watch-time is on mobile (GlobalMedia-Insight) and 92% of mobile video users share videos with others (Invodo) – yielding strong network effects

#2 Driver: Fixed Wireless Access (FWA)[1]
(32% of total traffic growth)

Image courtesy of CommSscope

- FWA connections rising to 360m in 2030 (4.3 connections per 100 capita, up from 1.6 in 2023)
- Traffic per FWA connection growing to 535GB per month –2.3x the level in 2023
- Increased availability and adoption of 5G FWA likely the main driver for the growth in total FWA adoption and traffic

Verizon and T-Mobile's 5G FWA customer targets would imply a 10% joint share of the US fixed broadband market by 2025 (GSMA, Mobile Economy 2023)

Note that FWA traffic is also driven heavily by video consumption. We include gaming, AR, VR and MR within the 'video' category[3], as well as future applications such as holographic or 3D content delivery. MR and 3D are discussed in later slides.

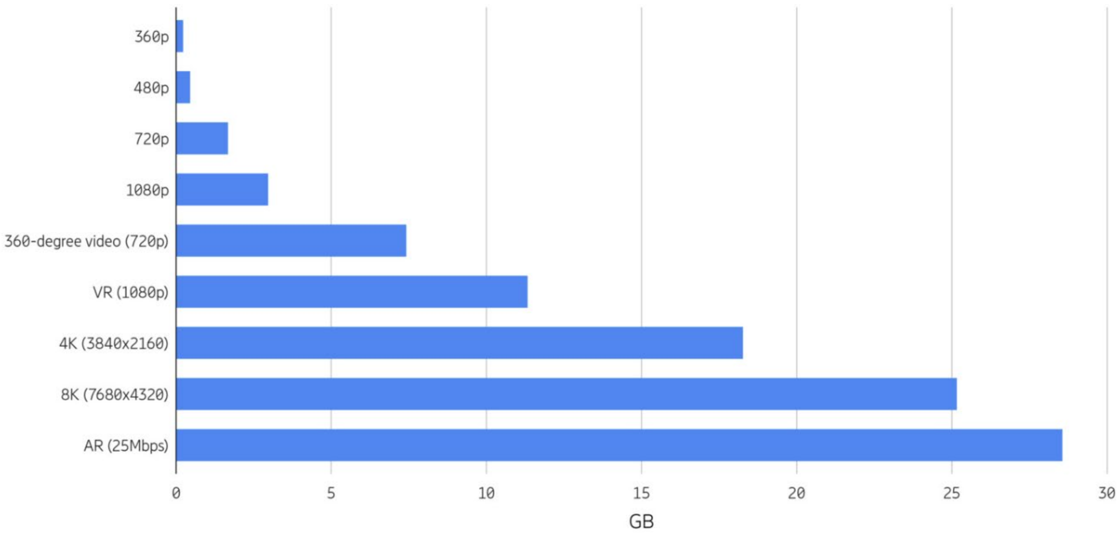
[1] *Quoted projections based on our geometric extrapolation of Ericsson forecasts to 2029.*
[2] *AR: augmented reality; VR: Virtual Reality; MR: Mixed Reality.*
[3] *Ericsson assumes that 'an initial uptake of XR-type services, including AR, VR and MR, will happen in the latter part of the forecast period".*

Impact of video resolution on data usage

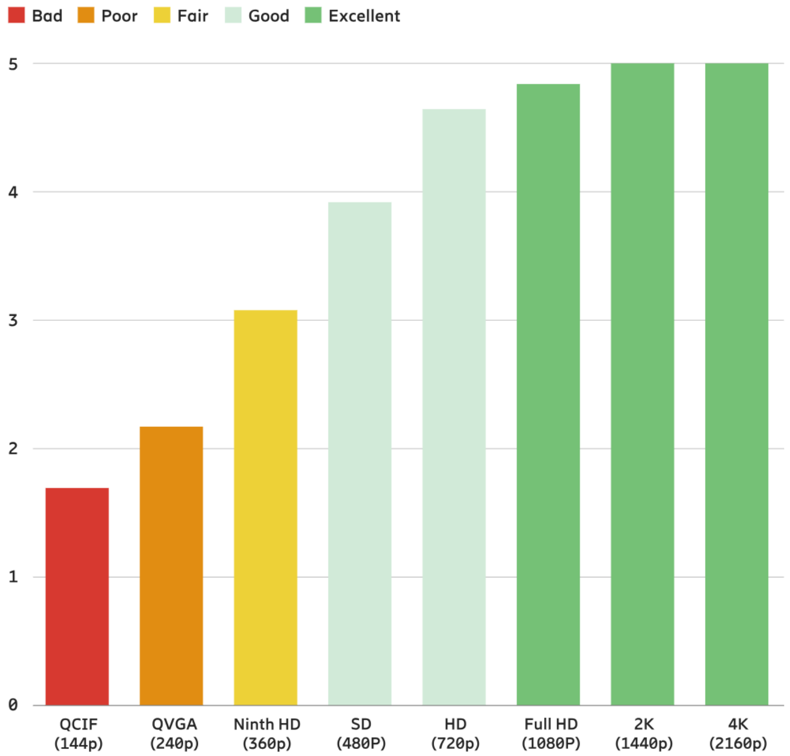
Streaming at a resolution of 720p already drives around 4x the traffic generated at a resolution of 480p.

Higher average video streaming resolution drive dramatic increases in traffic[1]

Monthly traffic from 5 minutes of streaming per day



Quality of experience vs mobile streaming resolution



- In 2018, most mobile video was streamed at low resolutions between 360p and 720p – largely due to restrictions by content providers and operators, as well as users selecting lower bit rates due to tighter data allowances
- These constraints are rapidly disappearing, with data allowances increasing dramatically or becoming unlimited

Raising the average from 480p (a plausible global average in 2023) to 720p (conceivable globally by 2030) would drive an almost fourfold increase in mobile video traffic from existing users

- In addition, smartphone penetration is growing (17% increase in connections over 2023-2030, with a 3.7x increase in 5G smartphones)
- Average screen-times excluding calls have also been on the rise (e.g. 2020-2023 CAGRs of 5.5% in China and 2.5% in the US[2])

[1] *Graphics, and data and commentary on typical streaming resolutions in 2018 from Ericsson*
[2] *Based on data sourced from Statistica.com (US) and Explodingtopics.com (China)*

A taste of things to come: glasses-free 3D video

After a burst bubble in 3D glasses and binoculars between 2010 and 2016, a new wave of glasses-free 3D devices is emerging.

The global 3D display market already exceeds $120 billion and is growing at a 19.2% CAGR[1]

- According to Transparency Market Research, 3D displays (primarily used in gaming, entertainment, advertising, and medical applications) will generate a global market worth $495 billion in 2031
  - Driven by the exponential growth of the gaming industry and the integration of AR and VR devices in consumer electronics
  - A rise in demand for 3D technology in innovative medical applications is likely to further boost market value
- Assuming an average cost of $1000 per device, the above could imply annual sales of 400 million units by the end of the decade –a significant proportion of which may rely on mobile for connectivity

The Lume Pad[2] by Leia Inc. retails at $499 in the US[2]

- Arguably, Leila offers the largest 3D ecosystem to date
- While only available in the US as of March 2024, the Lume Pad[2] 3D tablet is priced at a competitive mass-market level
- It boasts a 2.5K, 12.4'' screen, and allows 3D creation with in-built stereoscopic cameras

3D streaming on this device would consume up to 5x the data required for 720p and 20x that for 480p[3]

Wide adoption and extensive reliance relying on mobile connectivity could drive data consumption growth significantly above the forecasted 4x multiple by 2030

[1] Source: Transparency Market Research, Inc, April 2023
[2] Price quote and image from Leia Inc's website (leiainc.com/lume-pad-2) as of March 2024.
[3] Coleago estimate based on Ericsson data in the previous slide, assuming 3D video streaming at 8Mbps.

A taste of things to come: mixed reality

CEO Tim Cook compares debut of Apple Vision Pro to the birth of Mac, iPod and iPhone.

Apple fans line up to spend $3,499 on the Vision Pro Headset[1]

- CNET review: 'The **4K-resolution-per-eye**, micro-OLED display tech Apple uses is basically the 'retina' moment for VR and AR. It's vivid, richly coloured, HDR and just stunning'
- 180,000 units sold by January 2024 since the US launch in June 2023, despite a high current price
- Mass-market potential (plausibly before 2030) as unit prices fall with increasing scale and as competitor launch cheaper substitutes
- Headsets may be used in a mobile environment (e.g. in the back of cars, on trains, in cafes, in parks, etc.)

2x4K resolution would imply 15x more traffic than 720p and over 50x that with 480p[2]

[1] *Headline, image, Apple CEO quote and sales figures from Bloomberg article, 2 February 2024. All other images courtesy of Apple. Quoted CNET review from 30 January 2024.*
[2] *Based on Ericsson data in earlier slide.*

Future traffic drivers: mobile cloud applications

More rapid shifting of computational tasks from mobile devices to the cloud could drive growth in mobile traffic over and above the projections in preceding slides.

Key use cases may be found across:

- *Interactive services*
- *Collaborative tools*
- *Mobile gaming*
- *Mobile commerce and banking*
- *Social media (content sharing)*
- *Mobile healthcare*
- *IoT*

Mobile cloud computing (MCC) follows a wider trend towards the harnessing of remote processing power

- Complex mobile apps today perform tasks such as authentication, location-aware functions, and providing targeted content for end users – hence, they require extensive computational resources such as data storage capacity, memory, and processing power[1]
- MCC relieves the pressure on devices by shifting data processing and storage to shared cloud infrastructure
- Potential benefits of MCC include:
  - Reduced device power consumption, hence improved battery life
  - Extending the capabilities of devices that have lower processing power (e.g. for mobile gaming)
  - High scalability, and wider reach for mobile ap developers (less reliance on device capabilities)
  - Scalability and reach are further enhanced by the ability of mobile cloud apps to interact across environments using APIs[2], unlike native apps, that run on specific platforms such as iOS and Android
  - Seamless experience across platforms and devices such as desktops, mobiles, and tablets
  - Storing and processing data centrally, as well as the ability to share data with other applications, allow for improved real-time analytics
  - Sharing cloud-infrastructure drives cost efficiencies

Image courtesy of Simplylearn.com

- According to Mordor Research, the MCC market is growing at a CAGR of 25.3%, and will reach **$150 billion** by 2029 – with North America the largest market, and Asia Pac the fastest growing

Shifting data processing and storage to the cloud drives additional traffic to-and-from devices – this may become substantial over time, across smartphone, FWA as well as IoT use-cases

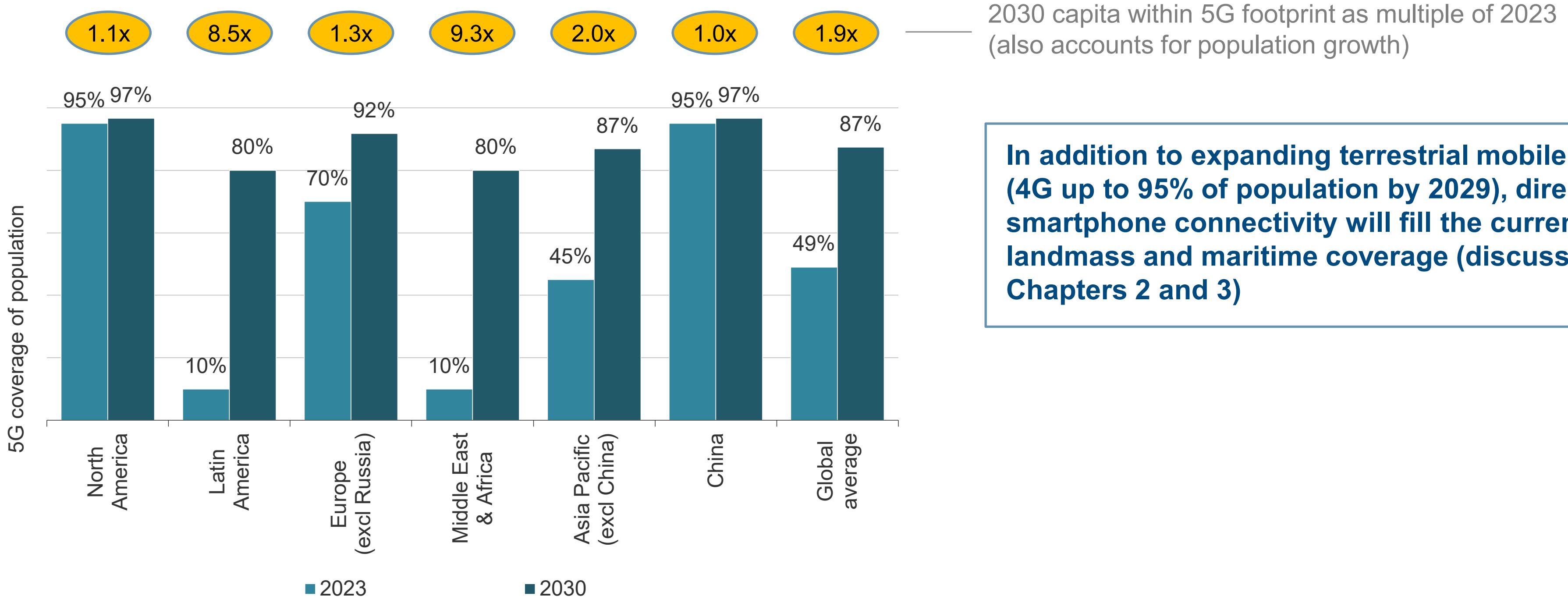
[1] *Source: aws.amazon.com/what-is/mobile-cloud-computing*
[2] *API: Application Processing Interface. APIs allow applications to function across different device operating systems (e.g. iOS, Android)*

Expanding network coverage is a key enabler of demand

The global population covered by 5G is projected almost to double between 2023 and 2030.

Increased terrestrial 5G coverage will underpin growth in 5G adoption and total data usage

5G population coverage in 2023 and 2030 by region[1]



In addition to expanding terrestrial mobile coverage (4G up to 95% of population by 2029), direct satellite to smartphone connectivity will fill the current gap in landmass and maritime coverage (discussed further in Chapters 2 and 3)

- Globally, Ericsson forecasts a moderate increase in global 4G coverage from (a high starting point of) 90% in 2023 to 95% in 2029 – representing a 6% increase in global capita within terrestrial 4G network footprints, taking population growth into account
- Versus a forecast rise in 5G terrestrial coverage from 45% of population in 2023 to 85% in 2029 (which we extrapolate to 87% by 2030) – with population growth, this would represent a 90% increase (almost doubling) in 5G covered capita worldwide

The moderate increase in 4G population coverage correlates with a modest increase in total smartphone penetration (see next slide), while the more dramatic rise in 5G coverage will support rapid increases in 5G adoption[2] – further underpinning growth in total data consumption

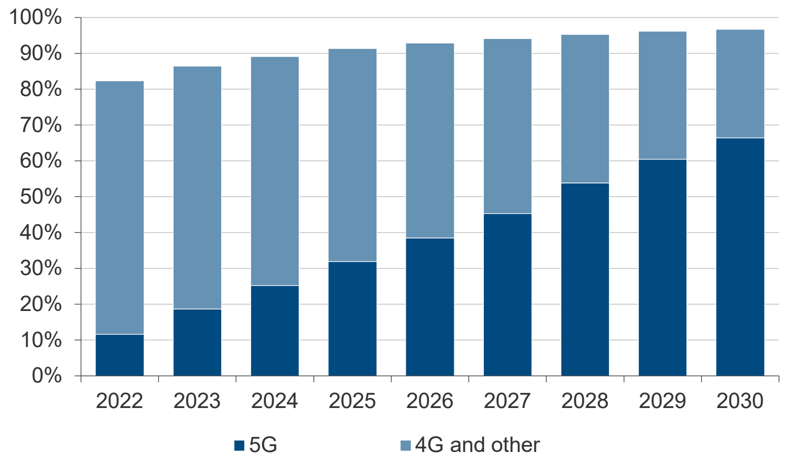
[1] Based on Ericsson regional estimates for 2023 and global forecast for 2029. 2030 forecast based on our own geometric extrapolation, with regional splits based on our approximate 'best fit'. On our population-weighted basis, we obtain a slightly higher global average in 2023 (49%) than Ericsson's rounded figure of 45%. *[2] Note that adoption rates will continue to increase organically within the original 5G footprint too.*

Global smartphone market evolution

By 2027, almost half of global smartphones will be 5G-enabled.

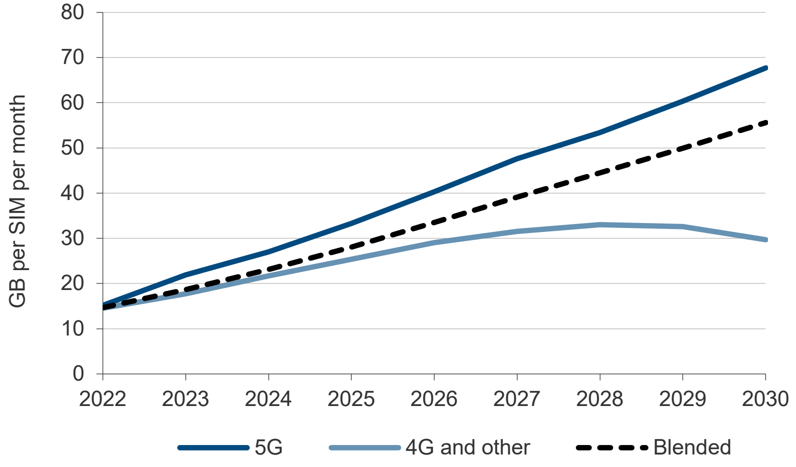
Moderate growth in global smartphone penetration, but significant rise 5G and in total usage[1]

Smartphone SIMs as % population



Data AUPU (GB per SIM)

AUPU: Average Usage per Unit



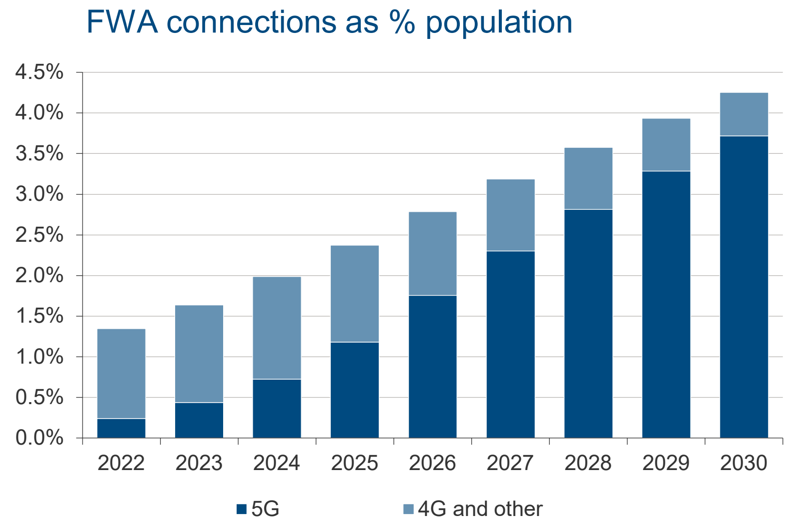
- Smartphones are projected to account for 88% of devices (excluding FWA and IoT) by 2030, up from 80% in 2023
  - Including growth in population, this yields a **17%** increase in the total number of smartphones (vs a 6% increase in 4G-covered pop)
- Almost half of global smartphones will be on 5G by 2027, rising to 69% by 2030
- The contribution per 5G smartphone to total traffic will be disproportionate: the resulting ratio of 5G to 4G and other AUPU (Average Usage per Unit) is projected to grow from 1.2x in 2023 to 2.3x by 2030
  - In earlier years, this ratio is suppressed by the fact that 5G smartphones also consume 4G and other traffic when 5G is unavailable, driving up AUPU attributed to legacy technologies[2]
  - The longer-term ratio is likely more representative of the uplift in usage from 5G devices: wider global 5G availability will reduce the distortion in our calculation of tech-based AUPU
- In 2030, on a blended basis, total mobile broadband traffic (excluding FWA) will reach 3.5x the level in 2023

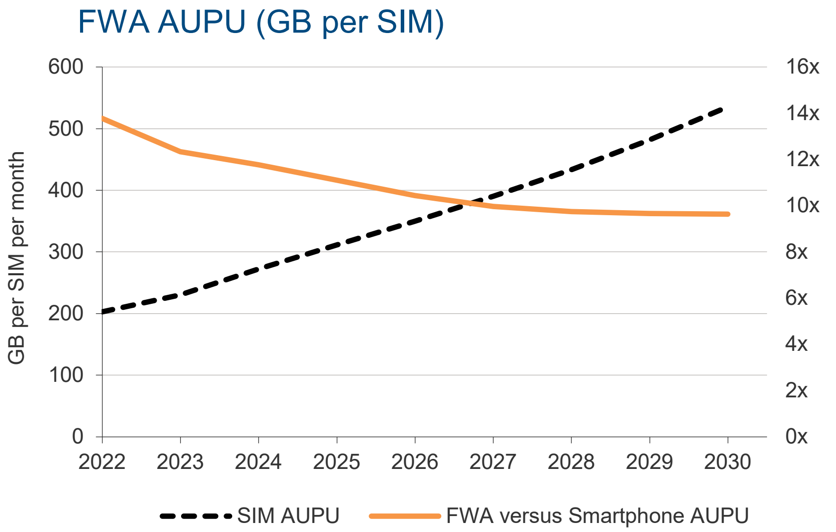
[1] Projections based on our geometric extrapolation of Ericsson forecasts to 2029, with population projections from the Word band.
[2] Our AUPU estimates are based on total projected mobile traffic excluding FWA divided by projected smartphones, respectively for 5G, legacy and on a blended basis.

Global FWA market evolution

There are far fewer FWA connections than mobile, but with unit traffic an order-of-magnitude higher than that traffic per smartphone.

High growth in global FWA penetration and traffic per connection[1]





- Global FWA connections will almost triple between 2023 and 2030 largely due to:
  - Increased availability of competitive offers on price and quality, especially with 5G fibre-like connectivity
  - No alternative in typically more rural areas where fixed broadband infrastructure is lacking or underperforming
  - Ideal solution for consumers and businesses whose primary locations are prone to change more frequently
- Half of global FWA connections will be 5G by 2025, rising to 87% in 2030 (versus 69% of smartphones)
- Average traffic per FWA connection is projected to reach 535 GB per month in 2023 – 2.3x more than in 2023, and almost 10x smartphone SIM AUPU
  - Strong FWA AUPU growth enabled by increased adoption of 5G FWA

Average global FWA AUPU in 2030 will approach current levels of Fixed Broadband consumption in high-income countries[2], which stands to reason: FWA is a substitute for wired broadband, so we may expect comparable usage rates over time, especially with 5G FWA

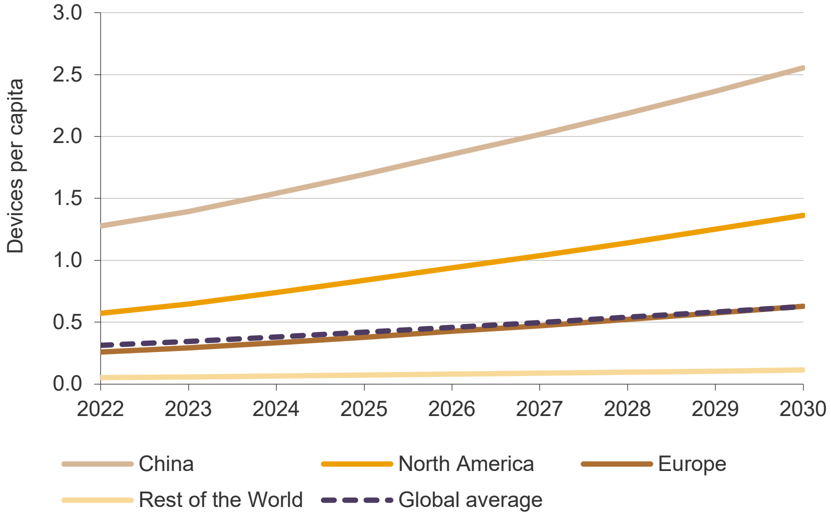
[1] *Projections based on our geometric extrapolation of Ericsson forecasts to 2029, with population projections from the World Bank.*
[2] *For example, OpenVault's Broadband Insights Report suggests US home internet usage reached 585 GB per month in Q4 2022..*

Global IoT market evolution

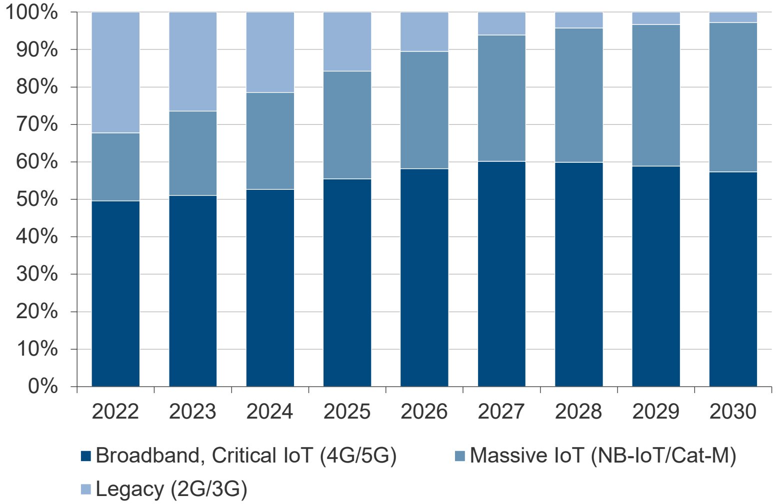
We anticipate a continued high growth in IoT connections, with China leading the way (2.5 devices per person in China in 2030)

Global cellular IoT connections will double between 2023 and 2030[1]

Cellular IoT connections per person



Mix of IoT connections



- Cellular IoT will reach a global average of 63 connections per 100 people worldwide, up from 34 in 2023 –a total of 5.3 billion units
- Yet, despite 9.6x projected growth in IoT traffic, the contribution to total traffic and connectivity revenues is likely to remain modest
  - According to IoT market research firm Berg Insight, global IoT connectivity revenues increased by 24% in 2022 to reach $13.9 billion globally (around 1.5% of total mobile industry revenues), and are projected to grow at a 15% CAGR to $27.6 billion by 2027
  - Applying this to the above IoT volumes yields average connectivity revenues per connection of $0.47 in 2022, rising to $0.56 in 2027
  - if IoT's share of mobile traffic were roughly aligned with its share of industry revenues, we would obtain a blended IoT SIM AUPU ranging from 0.84 GB/month in 2023 to 4.2 GB in 2030 – albeit wide differences would likely persist across IoT categories

Note that mobile IoT traffic on mobile networks could far exceed the levels implied by these external projections. Wearable IoT (such as body cams) could drive substantial consumption[2]. Moreover, requirements for low latencies and very high network availability for critical IoT imposes a far higher relative burden on mobile networks and may generate higher future IoT ARPUs than suggested above.

[1] Projected cellular IoT connections from GSMA, The Mobile Economy 2023. IoT mix taken from Ericsson's Mobility Report, November 2023. Note that Ericsson forecasts 25% more IoT connections than the GSMA by 2029 – we have taken the more conservative figures in our analysis.
[2] High-traffic wearable devices might be tethered to smartphones, placing their traffic within the MBB category.

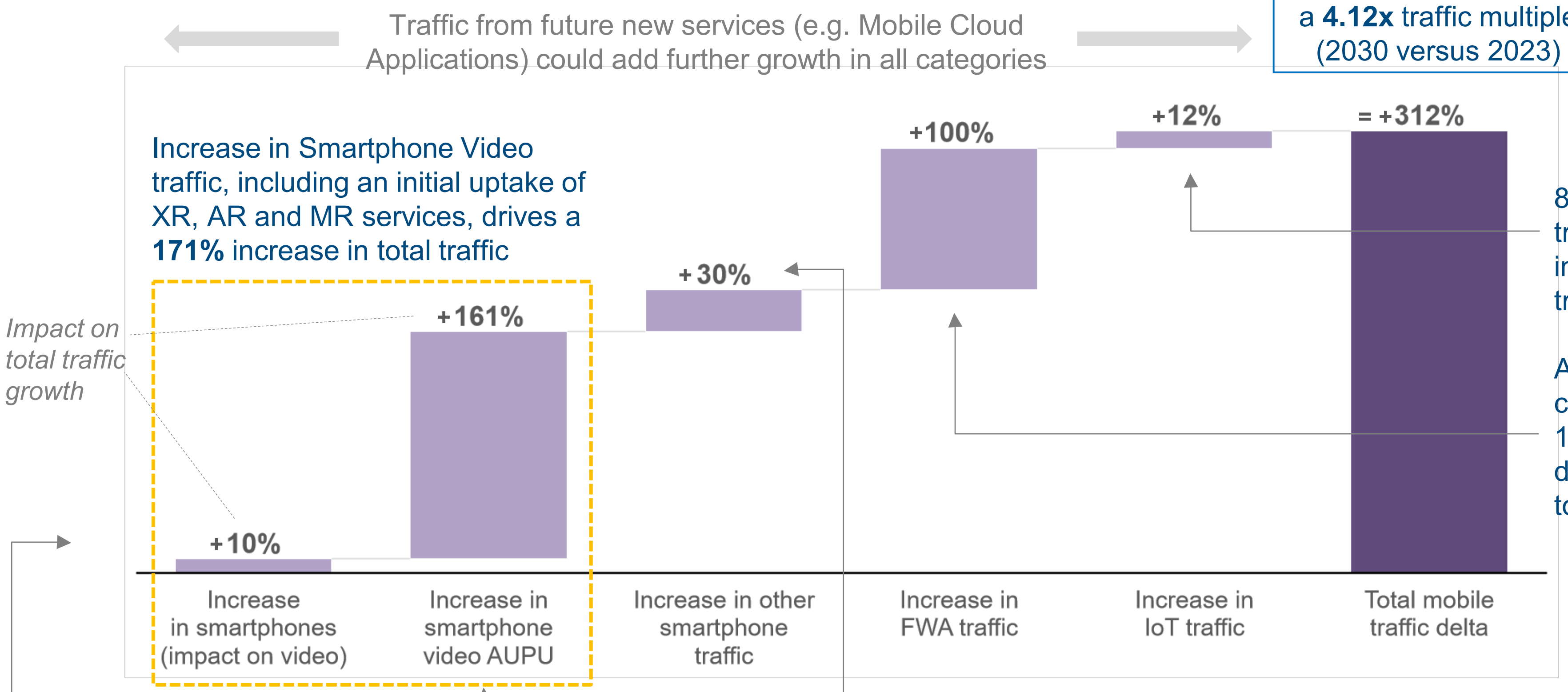
Breakdown of growth in global mobile data demand

Increased video streaming resolutions on smartphones contribute over half the growth in total traffic between 2023 and 2030.

Contributions to % increases in total mobile traffic 2023-2030

(not including private network traffic)

A 312% increase implies a **4.12x** traffic multiple (2030 versus 2023)



860% growth in IoT traffic drives a 12% increase in total traffic

A 160% rise in FWA connections and 130% rise in AUPU drives a 100% rise in total traffic

17% global increase in smartphones implies:

(1) More mobile video users (grows total traffic by 10%)

(2) Contributes to increase in other smartphone traffic[2]

A 237% increase in smartphone video AUPU is required to drive a 161% increase in total mobile traffic

– Growth in average resolution from 480p in 2023 to 684p in 2030 would achieve this[3]

– Highly plausible if one accepts 5G smartphones rising from 25% of all smartphones in 2023 to 83% by 2030

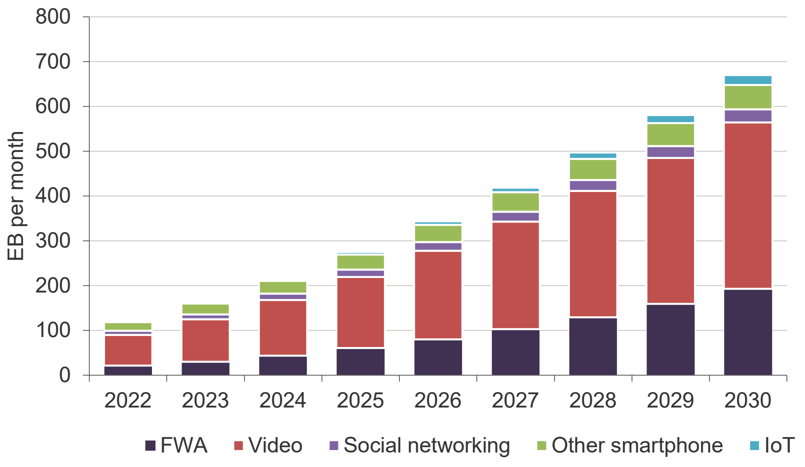
[1] *Private Network slices involve wholesale capacity rather than metered traffic* [2] *Rise in other smartphone traffic includes strong growth in social media usage, aligned to current trends (2.6x projected increase).* [3] *Illustrative calculation assuming average video streaming resolution is 480p in 2023, and based on Ericsson data on GB per hour of streaming at different resolutions*

Total projected global mobile traffic

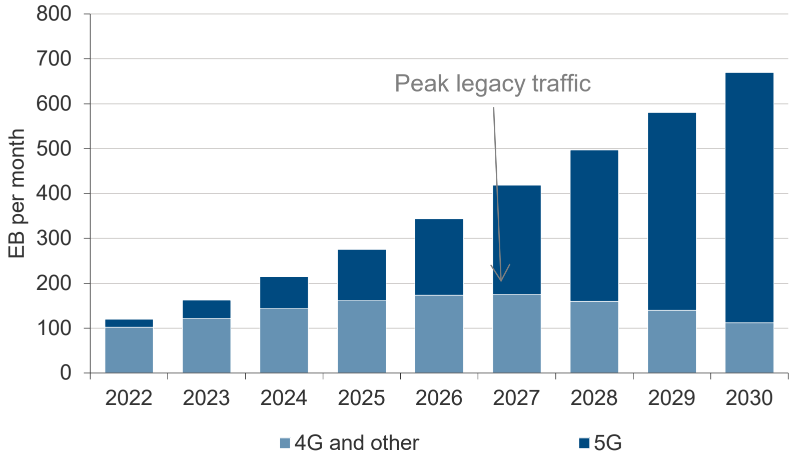
Four-fold increase between 2023 and 2030, with legacy-technology traffic peaking in 2027.

Dramatically increasing pressure on mobile network capacity, despite slowing rate of traffic growth[1]

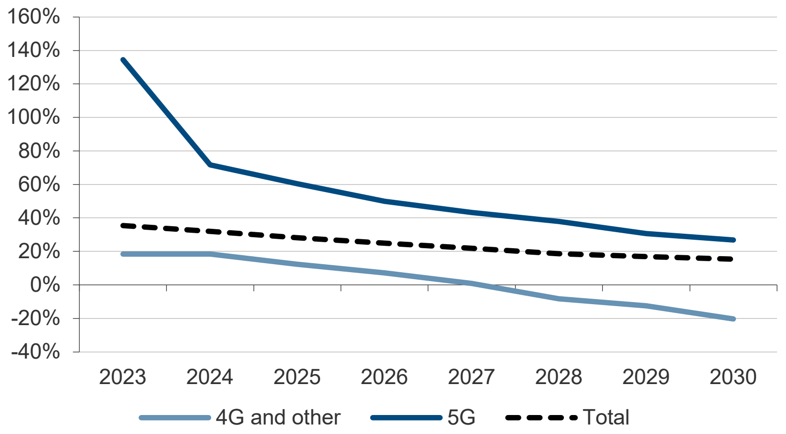
Total global mobile traffic by application-type



Total global mobile traffic by technology



Annual % change in total traffic



Note that rising traffic is only one of several aspects driving up the burden on mobile networks

- Wholesale bandwidth reserved to support private network slicing would constrain available capacity to serve direct mobile demand
- Data user speed experience targets will add significantly to the capacity operators need to provision per GB consumed (discussed in later slides within this chapter)

[1] *Projections based on our geometric extrapolation of Ericsson forecasts to 2029. 5G split of total traffic assumes the same ratio of FWA 5G AUPU to legacy-technology AUPU as that implied by Ericsson's projections for smartphone-based traffic..*

Impact of network coverage and service quality on demand evolution (1)

When analysing the evolution of mobile traffic, it may be helpful to isolate the influence of network coverage and capacity constraints on mobile adoption levels and consumption.

Traffic Development Index approach: methodology as applied in this report

Note: only IoT is directly quantified in the traffic forecasts

Mobile Broadband (MBB) index
Unconstrained adoption
× Unconstrained AUPU
= Unconstrained traffic → normalised

\+

Fixed Wireless Access (FWA) index
Unconstrained adoption
× Unconstrained AUPU
= Unconstrained traffic → normalised

\+

'New Services' index
Unconstrained adoption
× Unconstrained AUPU
= Unconstrained traffic → normalised

= Unconstrained total traffic index — *Index: 2023 = 100*

×

Network Suppression Factor (between 0 and 1)

↓

= Resulting traffic index (renormalised) — *Index: 2023 = 100*

- Each component (MBB, FWA and 'new services') is normalised to give an initial combined unconstrained traffic index = 100
- This enables relative contributions and evolution on an unconstrained basis to be quickly identified
- The network suppression factor represents the degree to which consumption is suppressed due to a lack of mobile coverage and (localised/temporary) congestion, which degrade the quality of user experience

As set out in the Introduction:

- A key objective of the TDI approach is to gauge levels of unmet demand, which has economic consequence for operators as well as social and economic consequences for the wider public
- Our starting point is actual data traffic - what is observed on networks. With the network suppression factor, which is estimated and projected directly, we work backwards to 'gross' (unconstrained) traffic across the three main categories (MBB, FWA and 'new services'), to obtain a complete picture

Impact of network coverage and service quality on demand evolution (2)

Coverage gaps mainly constrain adoption, while capacity short-falls mainly constrain consumption.

Network suppression index: key assumptions

For simplicity, we assume that:

- Population coverage affects adoption of all services, while congestion affects AUPU (Average Usage per Unit) for MBB and FWA[1]
- Adoption is linearly related to population coverage (e.g. 80% population coverage means adoption is 20% below its potential)[2]

Impact of coverage on adoption	2023	2030
4G coverage	90%	95%
5G coverage	49%	87%
Relative impact on overall adoption	-10%	-5%
Relative impact on 5G adoption	-51%	-13%

← Based on projections discussed in previous slides.

← For simplicity, we assume that 4G coverage affects overall mobile adoption, while 5G coverage affects the 4G/5G split.

Impact of congestion on AUPU	2023	2030
High-income markets	-8.0%	-5.7%
Emerging markets	-22.0%	-15.7%
Blended impact on global AUPU	-15.1%	-10.9%

← 2023 figures based on Huawei data[3]. Projected 2030 figures reflect the assumption that capacity-based traffic suppression will halve (linearly) over a decade.

The speed with which this occurs in practice will be significantly influenced by spectrum releases and other regulatory policies (see Chapter 3 and Part III).

Blended impact on total traffic	2023	2030
Net coverage impact	-13.5%	-9.0%
Net capacity impact	-15.0%	-10.6%
Combined impact	-26.4%	-18.7%

The above yields a blended network suppression factor of 0.74 in 2023 (26% of demand unmet), rising to 0.81 (19% unmet) by 2030 – suggesting that shortcomings in global network provision still have a substantial impact

[1] *Strictly speaking, poor coverage may have an impact on AUPU in all categories, and poor quality due to congestion may affect adoption.*
[2] *In practice, spending power and adoption rates are likely to be more concentrated in more densely populated areas that are already covered.*
[3] *For Emerging Markets, the factor ranges between -14%.and -30% within a sample of 9 markets. We applied the median for 2023.*

Impact of network coverage and service quality on demand evolution (3)

Reducing network coverage gaps and congestion is a further driver of consumption and revenues. It is also an important source of competitive advantage.

Policymakers have a major role to play in helping reduce network suppression (see Chapter 3 and Part III).

See Appendix A for detailed calculations

Unconstrained demand (2023 → 2030):

Traffic index = normalised, blended adoption x usage
Individual indices such as to add up to 100 in 2023

Note: only IoT is directly quantified in the traffic forecasts

Mobile Broadband (MBB) index
Total SIM penetration: 96% → 102%[1]
5G SIM penetration : 38% → 76%
4G AUPU: 21 → 33 GB/SIM
5G AUPU: 26 → 77 GB/SIM
Traffic demand index: 80 → 254

MBB: 80% of total demand in 2023
2030 index 254 = 80 x 3.1
3.1x blended demand growth to 2030

+

Fixed Wireless Access (FWA) index
Total SIM penetration: 1.8% → 4.5%
5G SIM penetration: 0.9% → 4.3%
4G AUPU: 255 → 284 GB/SIM
5G AUPU: 315 → 647 GB/SIM
Traffic demand index: 19 → 108

FWA = 19% of total demand in 2023
2030 index 108 = 19 x 5.7
5.7x blended demand growth to 2030

+

'New Services' index
IoT SIM penetration: 38% → 66%
IoT SIM AUPU: 0.8 → 4.2 GB/SIM
(note: tethered wearable IoT traffic is reflected in MBB)
Traffic demand index: 1 → 11

IoT = 1% of total demand in 2023
11x demand growth to 2030
2030 index 11 = 1 x 11

= Unconstrained total demand traffic index: 100 → 373 (3.7x) — *Index: 2023 = 100*

×

Constrained demand (2023 → 2030):

Note: coverage suppression will be mitigated by Satellite D2D, however our forecasts relate to terrestrial mobile traffic

Network Suppression Factor: 0.74 → 0.81
[= Coverage Suppression Factor[2]: 0.87 → 0.91
× Capacity Suppression Factor: 0.85 → 0.89]
Factor: 1.0 = no suppression

Renormalised such that 2023 index = 100

Resulting traffic index (renormalised): 100 → 412 (4.1x) — *Index: 2023 = 100*

Total SIM penetration: 86% → 97%
5G SIM penetration : 14% → 66%
4G AUPU: 18 → 30 GB/SIM
5G AUPU: 22 → 68 GB/SIM
Traffic index: 80 → 280
Mobile Broadband (MBB) index

+

Total SIM penetration: 1.6% → 4.3%
5G SIM penetration: 0.4% → 3.7%
4G AUPU: 217 → 253 GB/SIM
5G AUPU: 267 → 576 GB/SIM
Traffic index: 19 → 119
Fixed Wireless Access (FWA) index

+

IoT SIM penetration: 34% → 63%
IoT SIM AUPU: 0.84 → 4.2 GB/SIM
Traffic index: 1 → 14
'New Services' index

Same approach taken for constrained traffic indices as for unconstrained, but different results due to changing impact of network constraints on actual consumption

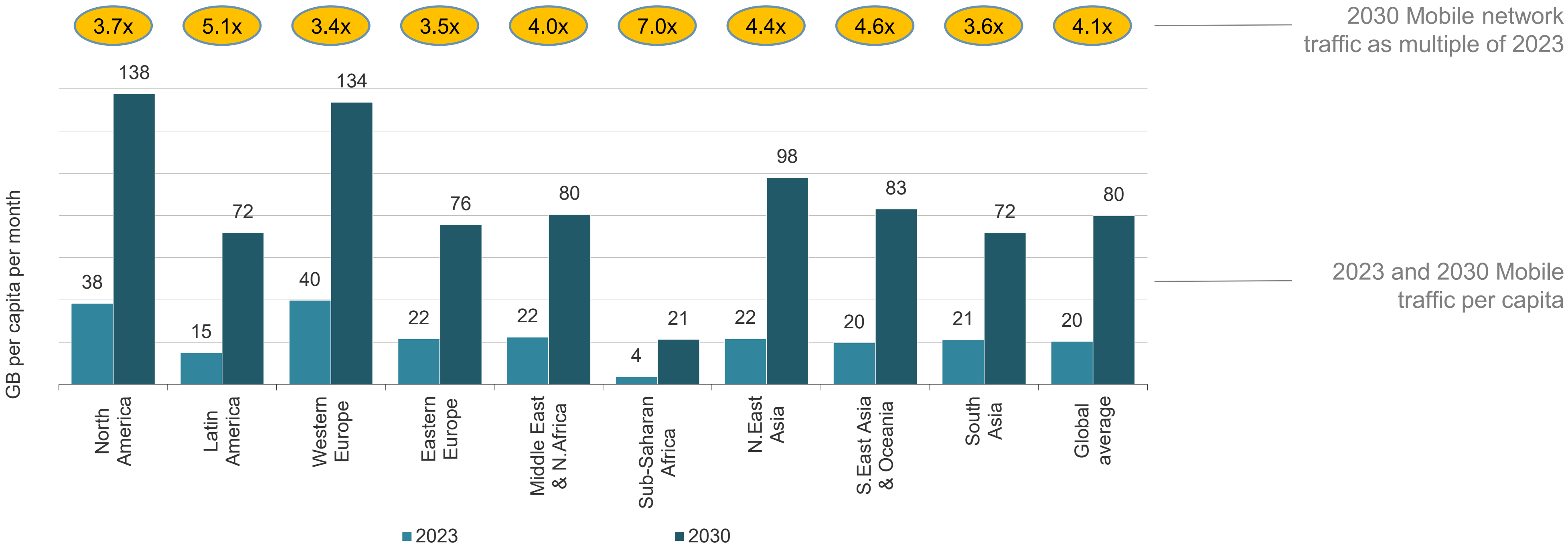
[1] *Note: SIM penetration includes the effect of multiple SIMs per human user*
[2] *Coverage Suppression Factor: impact on traffic (due to assumed impact of 4G and 5G coverage gaps on 4G and 5G adoption)*

Regional breakdown: total mobile traffic per capita

Depending on the region, total mobile network traffic in 2030 will be between 3.4x and 7x the 2023 levels.

Significant differences across regions, with higher growth rates in areas with lower traffic intensity[1]

Total mobile traffic per capita (GB per month) and total network traffic growth factors[2], including FWA



- Total traffic per capita allows for ready benchmarking of traffic intensities across different markets, albeit population growth needs to be factored into the calculation of total future mobile network traffic in individual markets
- Emerging market traffic intensity converging at different rates towards that in high-income countries, with sub-Saharan Africa growing fastest, followed by Latin America chiefly because they are well below global 2023 average.
  - Sub-Sahara projected traffic per capita in 2030 is close to the 2023 levels in Asia and Eastern Europe and South Asia. Growth drivers in Sub-Saharan Africa from 2023-2030 are likely to mirror those in Asia and Eastern Europe between 2016 and 2023

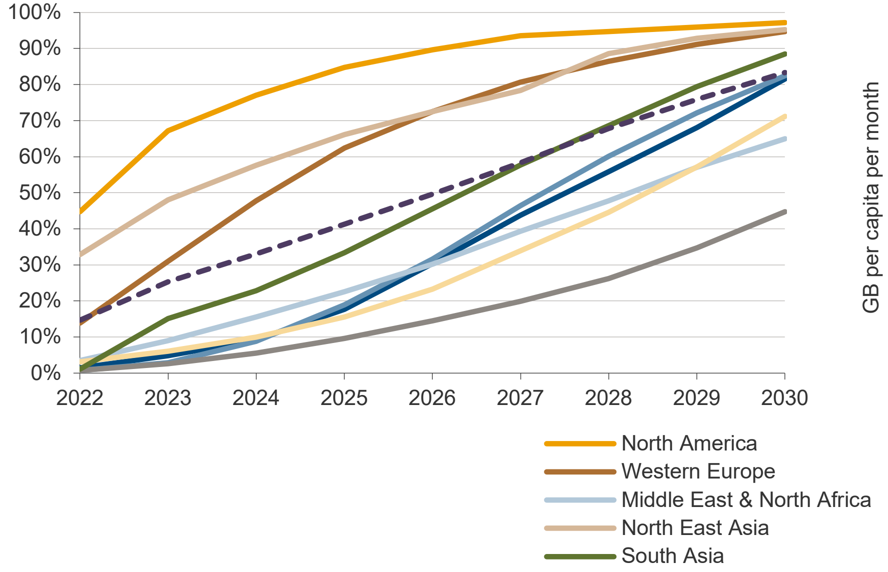
[1] Projections based on our geometric extrapolation of Ericsson forecasts to 2029, applying population forecasts sourced from the World Bank. Regional population and FWA traffic splits included in our analysis are based on our estimated best fit..
[2] The total network traffic growth factors reflect both the projected growth in traffic per capita and the population growth by region.

Regional break-down: 5G versus legacy traffic

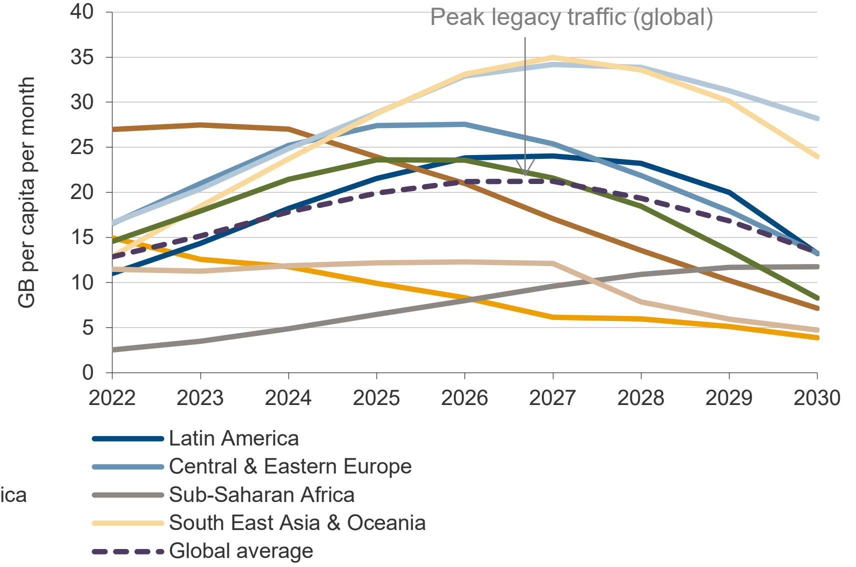
Continued growth in legacy traffic demand in many regions imposes constraints on the speed of spectrum refarming to 5G.

Globally, legacy mobile traffic will peak in 2027 – in sub-Saharan Africa however, 4G and other demand will grow beyond 2030[1]

% of total network traffic 5G



Legacy (4G and other) traffic per capita, in GB per month



Legacy traffic peak year and growth from 2023 to peak

Region	Growth to peak	Peak year
Latin America	41.3%	2027
Central & Eastern Europe	34.0%	2026
Middle East & North Africa	32.5%	2028
South-East Asia & Oceania	43.3%	2027
South Asia	44.7%	2026
World	36.8%	2027

- Legacy demand has peaked or is peaking in North America, Western Europe and North-East Asia, although this might not be the case for all individual countries in these regions
- Significant growth in legacy demand between 2023 and the peak year – 37% on average across the globe
  - In sub-Saharan Africa, legacy data traffic in 2030 will reach 4x the 2023 level
- This demand needs to me managed alongside the (more rapidly) growing demand for 5G

[1] *Projections based on our geometric extrapolation of Ericsson forecasts to 2029, applying population forecasts sourced from the World Bank. Regional population and FWA traffic splits included in our analysis are based on our estimated best fit..*

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Differentiation in an age of unlimited mobile plans

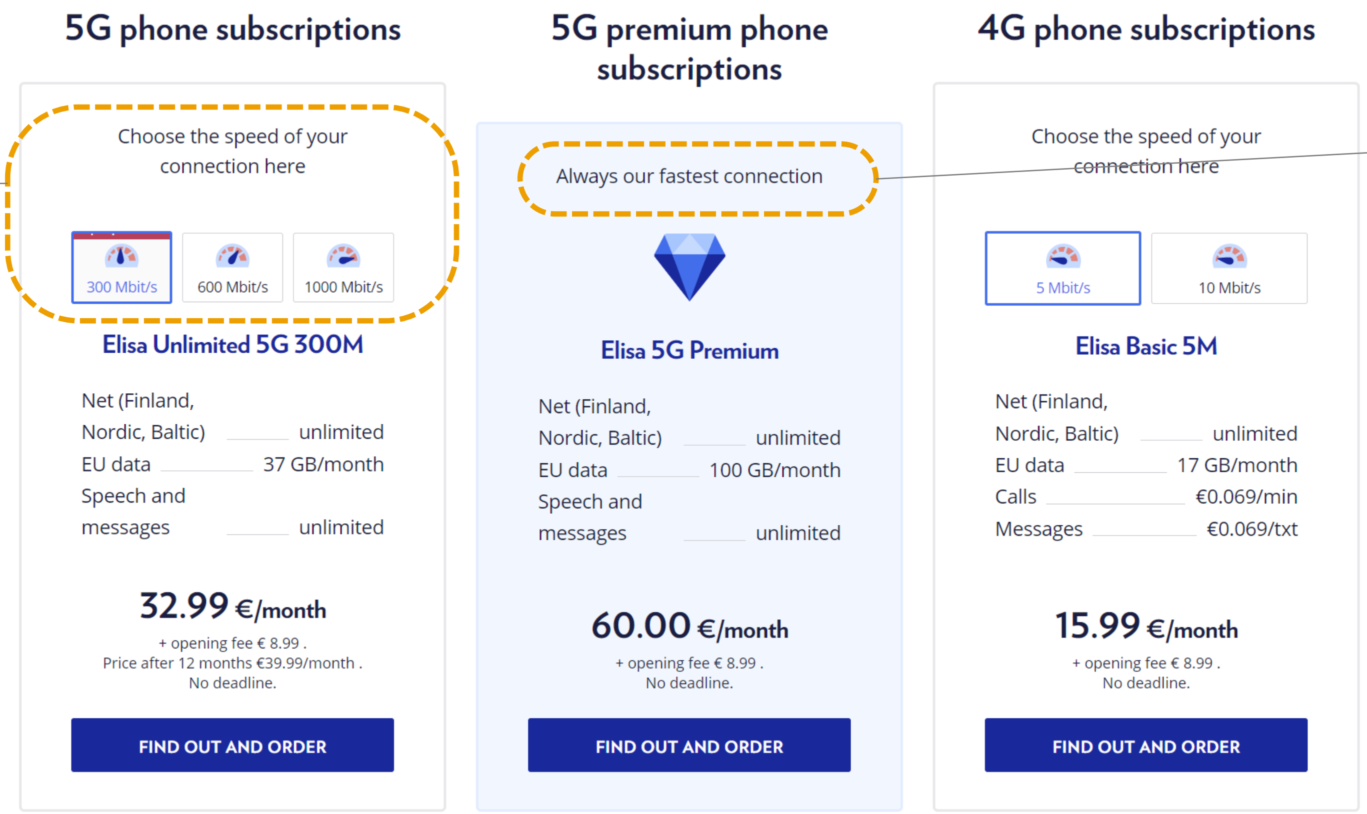
Over 60% of mobile 5G service providers have at least one Unlimited Data package in their offering[1].

Mobile operators will continue shifting from selling data volumes (in GBytes) to selling mobile data speeds (in Mbps)

- With unlimited mobile price plans increasingly common, the main remaining option is to differentiate offerings based on data speeds
- Finland has been leading the way with unlimited packages since around 2015, with Elisa launching speed-based offers around 2016
- Mobile speed-based pricing is still far from the international norm, however, which suggests a missed opportunity (see Chapter 3)

Elisa Unlimited Plans in Finland

Prices range from €32.99 for speeds capped at 300Mbps to €49.99 for rates up to 1000Mbps



From Elisa website (February 2024, translated by Google)

Premium Plan: always the fastest available speeds (up to 1.2Gbps)

€10/month premium over the 1000Mbps unlimited plan

This suggests Elisa may prioritise Premium customers' access to bandwidth in areas and times of network congestion

[1] *Ericsson Mobility Report, November 2023, based on a survey of 308 mobile service providers (network operators and MVNOs).Slightly less than 20% of mobile SPs that do not offer 5G include unlimited data plans, yielding an average of 45% offering unlimited among all SPs.*

Mobile speed-based pricing: key challenge

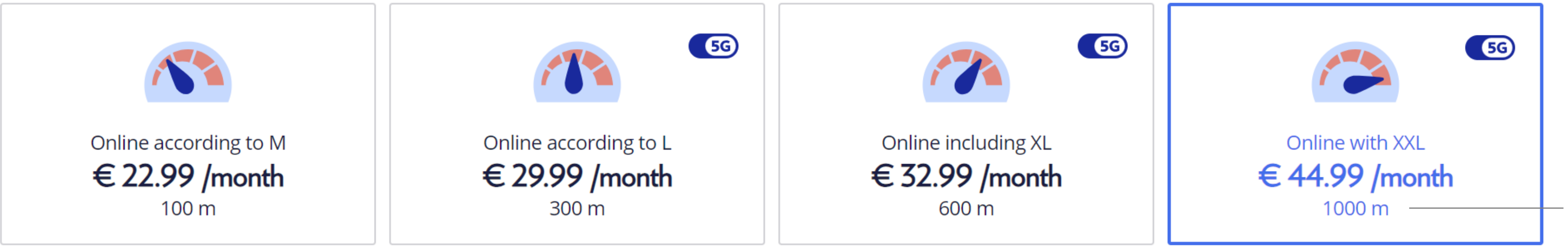
Speed guarantees are more difficult to implement within contended access networks such as mobile.

Nevertheless, selling prioritised access to mobile bandwidth is a feasible alternative (see Chapter 3)

Mobile speed-based pricing would mirror fixed broadband

- Fixed broadband offers in mature markets are typically quoted from a minimum guaranteed speed up to a maximum rate in Mbps
- Key differentiator between fibre broadband, hybrid fibre/coax and legacy copper

Elisa FWA pricing in Finland



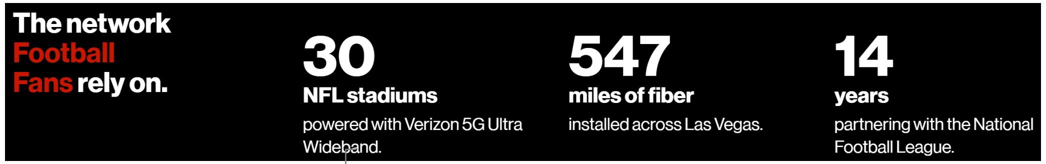
Speed limit in Mbps

From Elisa website (January 2024, translated by Google)

However, minimum speed guarantees are more difficult for mobile operators to offer (especially to smartphone users)

- The mobile access network is contended (no dedicated links), so available speeds will depend on the number of concurrent users within a site-sector relative to available sector capacity
- Network quality for smartphone-eMBB users likely to vary significantly across locations (e.g. urban versus rural, indoor versus outdoor)
- In these circumstances, defining and communicating minimum speed guarantees for mobile users presents a significant challenge

Elisa's offers based on speed caps do not represent pure speed-based pricing in the fixed-broadband sense. Yet these do provide a degree of speed-based differentiation, and we also see operators elsewhere emphasising speed performance. An example is Verizon with its advertising around the Super Bowl.



From Verizon's website (February 2024)

Emphasising 5G Ultra Wideband in NFL stadiums

Impact of speed experience targets

The objective of 5G is a 'fibre-like' experience. However, it is more costly to produce a faster bit then a slow ('best effort'[1]) bit.

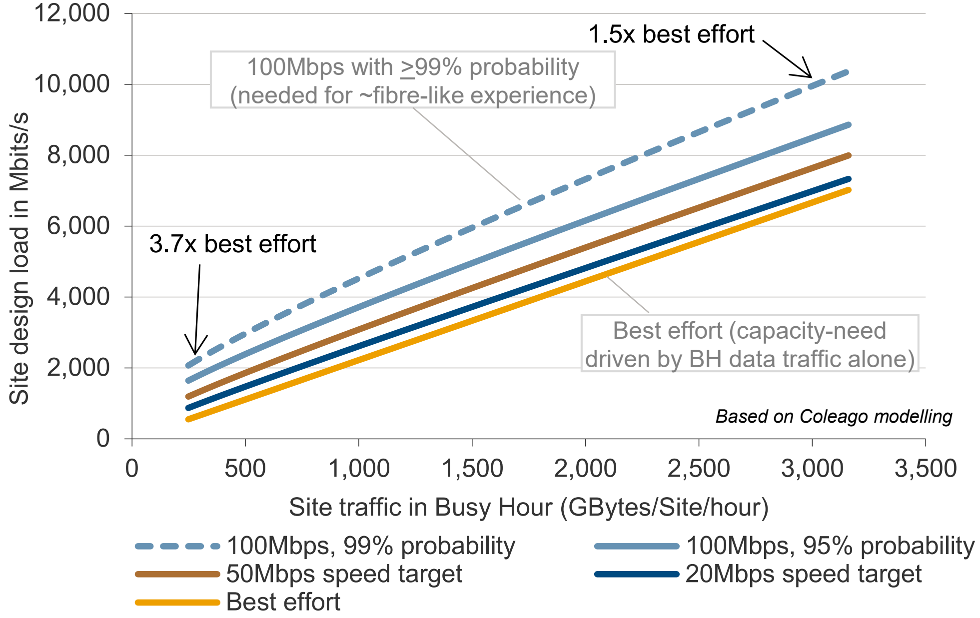
The ITU IMT-2000 (5G performance) requirements specify a 100Mbps, 'fibre-like' user-speed experience

- This reflects customer needs for higher data speeds to deliver an adequate broadband experience
- But a 'fast bit' of mobile data is more expensive to deliver than a 'slow bit': it requires greater network capacity
- Illustration: 2x as much capacity would be needed to deliver 100MB each to two users in the same second than one second apart
- 100Mbps speeds need to be delivered at least 99% of the time to start approximating fibre-like consistency

5G Network performance requirements

	Throughput	Latency	Area capacity	Mobility
eMBB	50-100Mbit/s	20ms	-	-
Gaming at 1080p, 60FPS	50Mbit/s	<20ms	-	-
Gaming at 2k, 60FPS	100Mbit/s	<10ms	-	-
Gaming at 4k, 60FPS	200Mbit/s	<5ms	-	-
FWA	up to 1Gbit/s	<5ms?	-	N/A
IMT Advanced (ITU)	10Mbit/s	10ms	0.1Mbit/s/m^2	350Km/hr
IMT 2020 (ITU)	100Mbit/s	1ms	10Mbit/s/m^2	500Km/hr

Impact of minimum data-speed targets on capacity requirements



Due to statistical effects[2], the % impact of speed targets on capacity-need is lower where traffic intensity is higher

Relative to 'best effort'[1], we estimate that a **100Mbps** speed experience target delivered with **99% probability** drives a:

- **~3.7x** increase in capacity need where traffic intensity is low
- **~1.5x** increase in capacity need in the busiest areas (such as in dense urban locations)
- **~2x** estimated increase in average capacity need across the entire network

[1] 'Best effort' data provision means delivery of a given quantity of GBytes during the busy hour without regard to data-speed experience requirements. [2] To illustrate this point simply, catering for an increase from 2 to 3 concurrent users in a cell imposes a far greater % increase in capacity (+50%) than, say, from 10 to 11 (+10%).

From traffic to demand for capacity

A consistent 100Mbps speed experience target roughly doubles average network capacity-need.

The combined effect of traffic growth and any data speed targets is substantial

- **4x** more capacity is needed to meet 4x growth in traffic (the global average for 2023-2030) on a best-effort basis[1]
- A 100Mbps target (with 99% probability) roughly doubles capacity-need across the network implying an ~**8x** capacity multiple
  - And a ~**6x** capacity multiple in dense urban areas (because the uplift is lower than average in high traffic-intensity areas, as discussed in the previous slide)

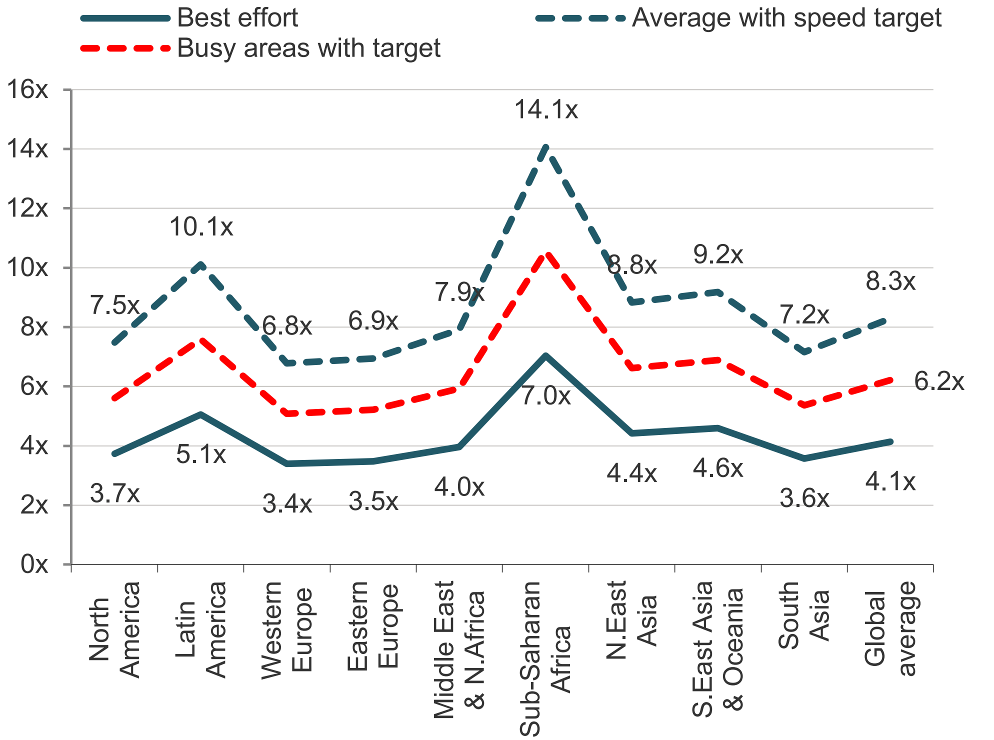
Western Europe (lowest TDI growth):

- 3.4x more capacity needed on a best-effort basis
- **~7x** more across the network to meet the 100Mbps speed target
- **~5x** more in busier areas (dense urban) to meet the speed target

Sub-Saharan Africa (highest TDI growth):

- 7x more capacity needed on best-effort basis
- **~14x** more across the network if the 100Mbps speed target is met by 2030, and **~10x** more in busier areas (dense urban)

Capacity-need by region (2030 vs 2023), for a 100Mbps speed-target with 99% probability of achieving it[2]



Note: our analysis does not address capacity-need for private network provision (using network slicing – see next slide).

How future capacity needs can be met is discussed in Chapter 3 (with an illustration for developed markets in dense urban areas)

Separately, we address IMT spectrum needs from a societal perspective in Chapter 5

[1] *While there may be spare capacity in some areas, our modelling suggests that % increases in deployed capacity align broadly with % increases in traffic.*
[2] *Note that our analysis is intended to show the impact of a consistent 100Mbps target on capacity-need. We recognise that such targets may not be delivered in every market, with Emerging Markets clearly less likely (at least by 2030).*

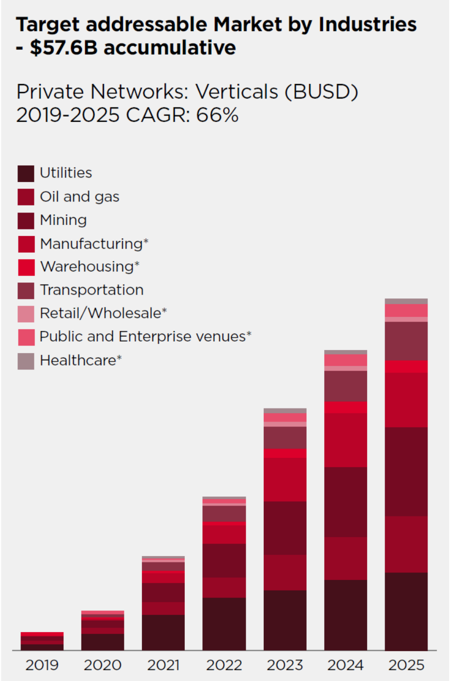
Emerging segments: private networks

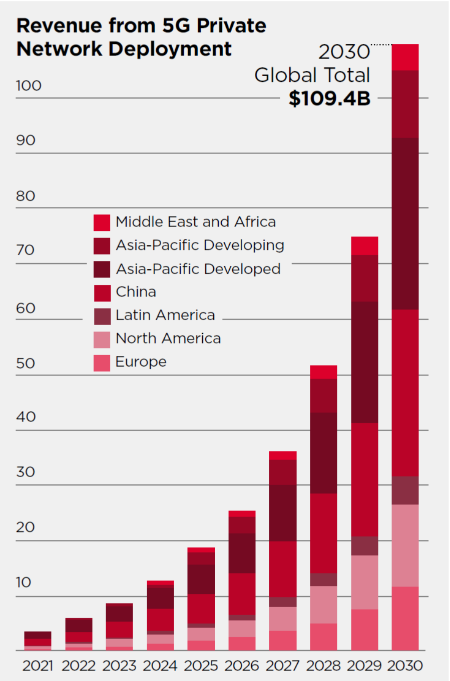
5G private networks are projected to contribute almost 10% to mobile operator revenues by 2030.

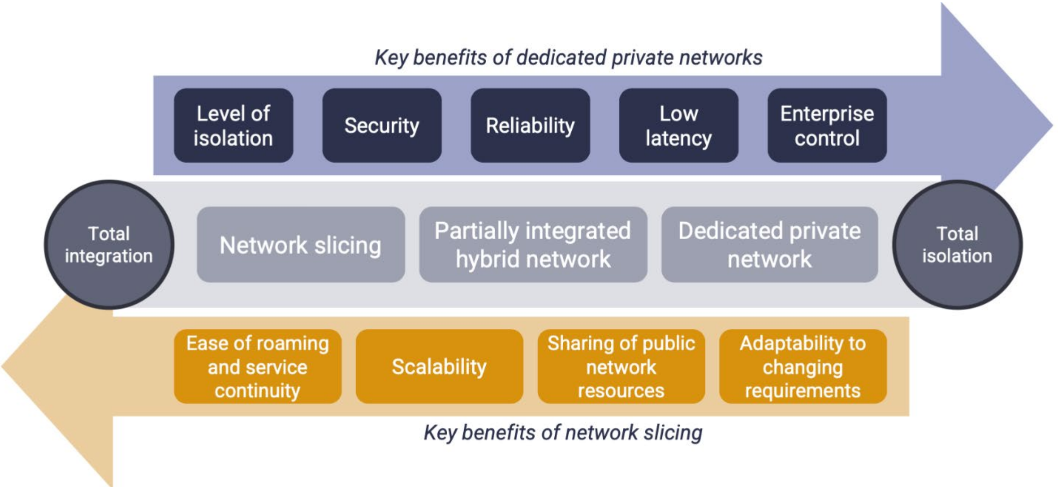
Hybrid solutions and network slicing involve the provision of wholesale capacity.

Industry 4.0 and digital transformation are driving private mobile network (PMN) deployments across industries and enterprises[1]

- Rapidly growing segment – 4000 5G/LTE PMNs in 2022, projected to grow to 60,000 by 2028 (Analysys Mason)
- Key drivers for enterprise:
  - Privacy and security
  - Enterprise control
- Key drivers for industry:
  - Ultra-low latency and network reliability
  - Aggregation of high volumes of critical and high bandwidth data
  - Networking and coordination of manufacturing equipment – allowing equipment such as mobile robots and automated guided vehicles (AGV) to be shared efficiently across production lines
- Deployment options include dedicated networks, 5G network slicing (see Chapter 2), and hybrid solutions that combining both







5G network slicing will allow mobile operators to address the PMN market cost-effectively (including the hybrid segment):

- Slicing is less costly because this allows sharing of existing network resources
- It is suitable for many use-cases, is highly scalable, and can readily be integrated within a hybrid context
- It offers highly flexibility and adaptability
- It helps customers ride the technology curve towards 6G

[1] *Projections, segmentation and commentary on PMN drivers for industry from GSMA (Private 5G Industrial Networks, June 2023). Graphic on relative benefits of dedicated PMNs versus network slicing from STL Partners (stlpartners.com). Projected growth in the number of MNPs from Analysis Mason, January 2024.*

Emerging segments: mobile Fintech

Mobile Fintech offers an opportunity to compensate for a widespread lack of growth in connectivity revenues.

Mobile operators are well placed to drive and benefit from increased financial inclusion

- Increased smartphone adoption and affordable connectivity paves the way for innovative mobile-based fintech solutions
- Mobile Fintech is one of the fastest growing segments. However, mobile operators need to move quickly to capture a share of the emerging value, in the face of pressure from innovative OTT solutions
- Operators' key strength is likely to remain centred on their customer relationships and connectivity coverage, but they may need work with specialised third-parties to harness the Fintech opportunity

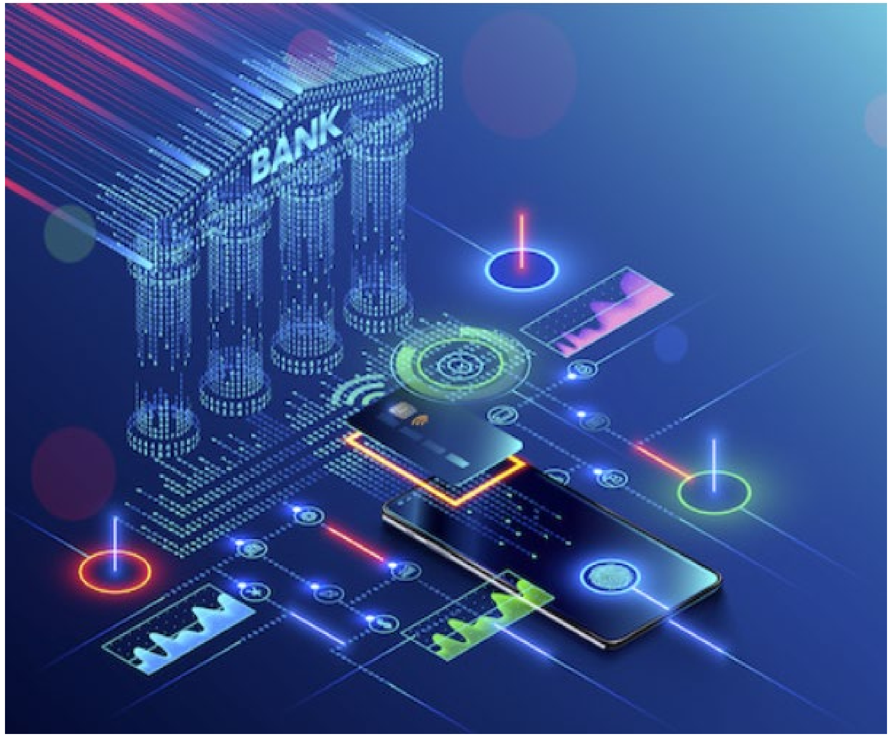


Image courtesy of FintechFutures.com

Notable mobile Fintech successes have been achieved in emerging markets, but initiatives are also being pursued in high-income countries:[1]

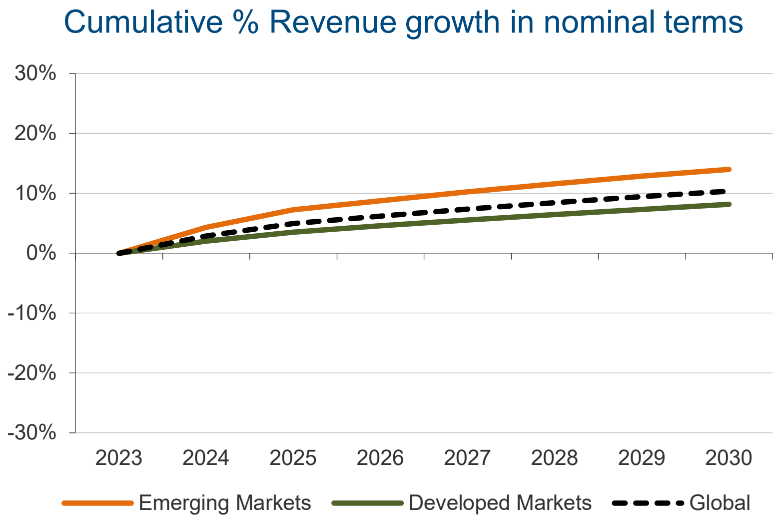
- Mobile money and digital wallet platforms launched by MTN, Safaricom, Tigo and Turkcell over the past decade contribute in excess of 10% of total revenues in several markets
  - e.g. M-Pesa now accounts for 38% of Safaricom's service revenues
- STC Pay boasts nearly 10m customer accounts across MENA
- Digital banking service Orange Bank has nearly 2 million customers in Europe and 800,000 in Africa
- During 2023, Zain's fintech revenues grew to 3.4x the level in 2022[2]
- MTN and Mastercard announced a partnership to enable Mastercard's virtual cards to be linked with MTN's MoMo wallets in 2023
- In August 2023, Mastercard and Airtel Africa announced the launch of a new cross-border remittance service
- Verizon and Mastercard formed a strategic alliance in 2021 to bring 5G to the global payments industry

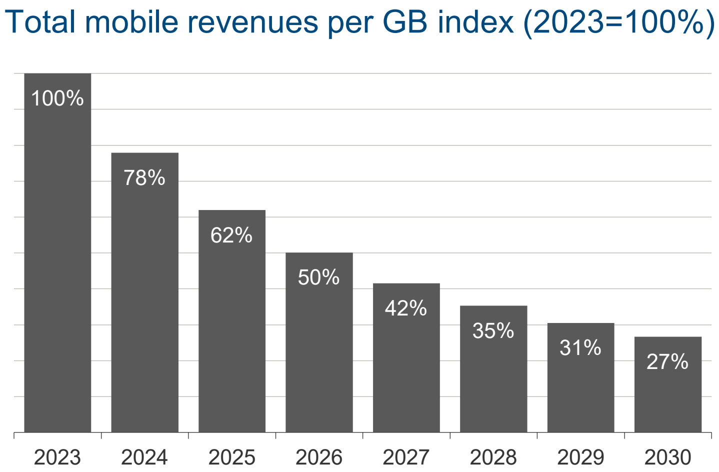
[1] Examples from GSMA The Global Mobile Economy 2023 and The Mobile Economy Sub-Saharan Africa 2023
[2] Zain Group Q4 2023 investor presentation

Global industry revenues

Simply to break even, total global industry costs per GB would need to fall to 27% of current levels.

Evolution of mobile industry revenues between 2023 and 2030[1]





- The GSMA projects total global industry revenues rising from $1.1 trillion n 2023 to $1.2 trillion in 2030 (1.4% CAGR)
  - Developed markets: from circa $680m to $735m (1.1% CAGR)
  - Emerging markets: from circa $420m to $480m (1.9% CAGR)
- In real terms, however, total industry revenues in both the developed and emerging market segments are projected to fall
  - IMF forecasting 2023-2028 inflation growth at a 2.1% CAGR in developed economies (1.8% in 2028) and 5.7% CAGR in emerging economies (4.9% in 2028)
  - GSMA forecast suggests the trend of broadly flat or declining real-term revenues in recent years will persist

In the face of rapidly rising network capacity requirements, the GSMA projections, if correct, would indicate ongoing pressure on industry returns – unless operators are able to reduce their total costs per GB consumed in line with the steep fall in revenues per GB.

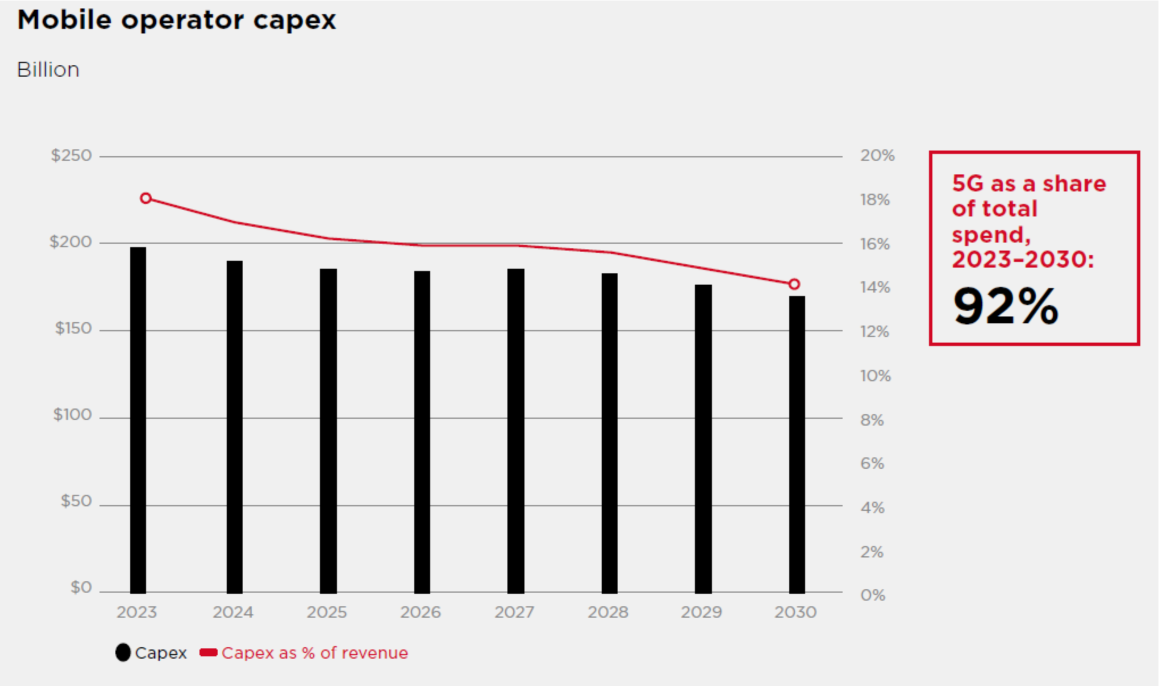
[1] Industry revenue projections in nominal terms from GSMA, The Mobile Economy 2023. Total revenues per GB obtained by dividing GSMA's global revenue forecast by total industry traffic projected in previous slides. Inflation forecasts based on IMF World Economic Outlook, October 2023.

Outlook for industry profitability

With average annual mobile capex projected to average 16% of annual revenues between 2023 and 2030, pressure on industry returns is likely to persist.

GSMA projections suggest a total of $1.5 trillion in global industry capex between 2023 and 2030[1]

- GSMA projections imply capex averaging 16% of projected global industry revenues over the period, with the overwhelming bulk of spend focused on 5G
- Compared with earlier projections of a 17% ratio of network investment to revenues between 2020-2025, these latest forecasts suggest a slight improvement
- This ratio is projected to fall most significantly in the tail end of the forecast horizon to close to 14% in 2030
- However, the cost of incremental spectrum remains uncertain, and unduly high future licence costs could offset any relief from any reduction in the relative burden of capex
- More extensive sharing of (passive) assets such as tower infrastructure across the industry could help address the both the capex and opex challenges facing operators



Revenues minus Capex are set to improve slightly – the key is to contain increases in opex

- GSMA global projections suggest that revenue minus capex will grow at a 2.1% CAGR between 2023 and 2030
- This would yield a slight improvement in real terms, before opex and any additional spectrum costs are taken into account
- Opex tends to be inflationary across all cost categories, and is heavily influenced by total mobile site count (macros and small cells) – which is likely to grow significantly with increased demand for capacity

Pressures on industry returns are thus likely to persist – the implications for operators as well as policy makers are discussed in Chapter 3

[1] *Projections and graphic from GSMA, The Mobile Economy 2023.*

Networks and Technology

Key developments shaping the mobile landscape

2

Timeline from 4G, 5G to 6G

Mobile technologies follow an approximate 10-year cycle.

Standardisation, deployment and development timelines

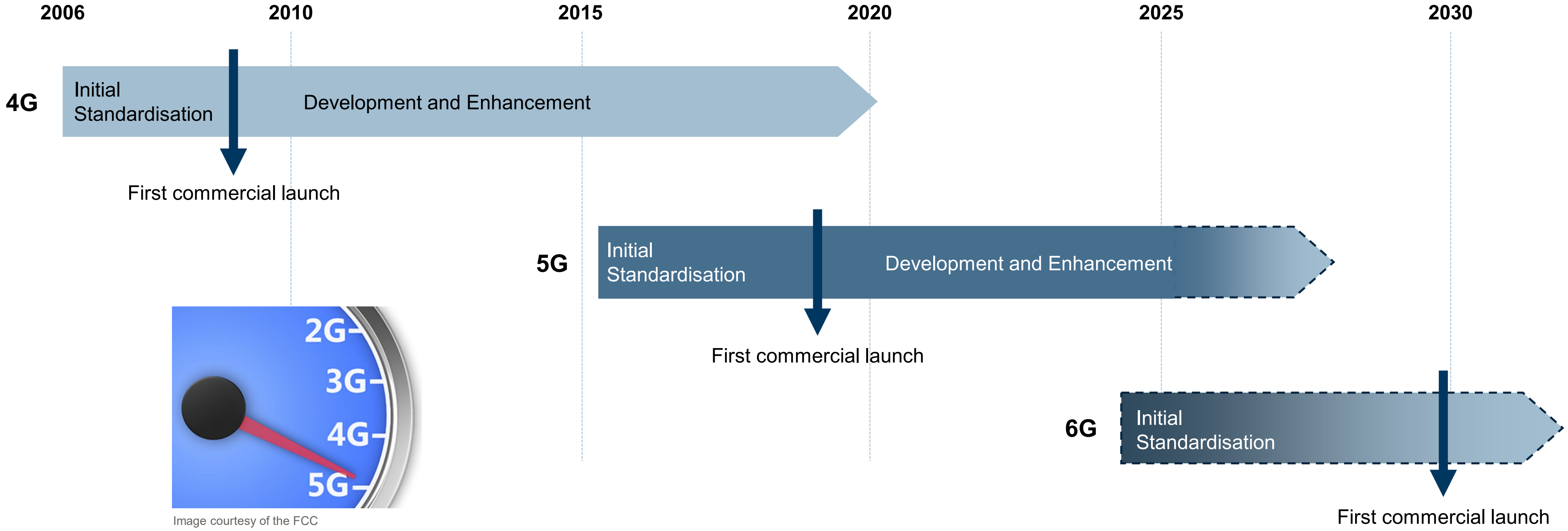


Image courtesy of the FCC

- Mobile technology has followed an approximate 10-year cycle: 2G (GSM) debuted commercially in 1991, followed by 3G 2001, 4G in 2009, and 5G in 2019. The first 6G networks are expected to launch in around 2030
- Although commercial launches are dated at these times, standards development and enhancement continue for several years afterwards
- Noteworthy advancements have emerged from these efforts. For instance, 4G Advanced was finalised in 2011, enabling higher data rates (up to 1Gbps, compared to 4G's maximum of 100Mbps) through technologies such as carrier aggregation
- Similarly, 5G Advanced is expected to be finalised in 2024 and introduces various innovations such as the introduction of Artificial Intelligence (AI) and Machine Learning (ML) into the network and its operation – laying essential foundations for 6G

5G Primer for non-specialists

While the leap from 3G to 4G was more significant than that from 4G to 5G for the bulk of mobile customers, 5G still represents a step-change in network efficiency.

5G versus 4G

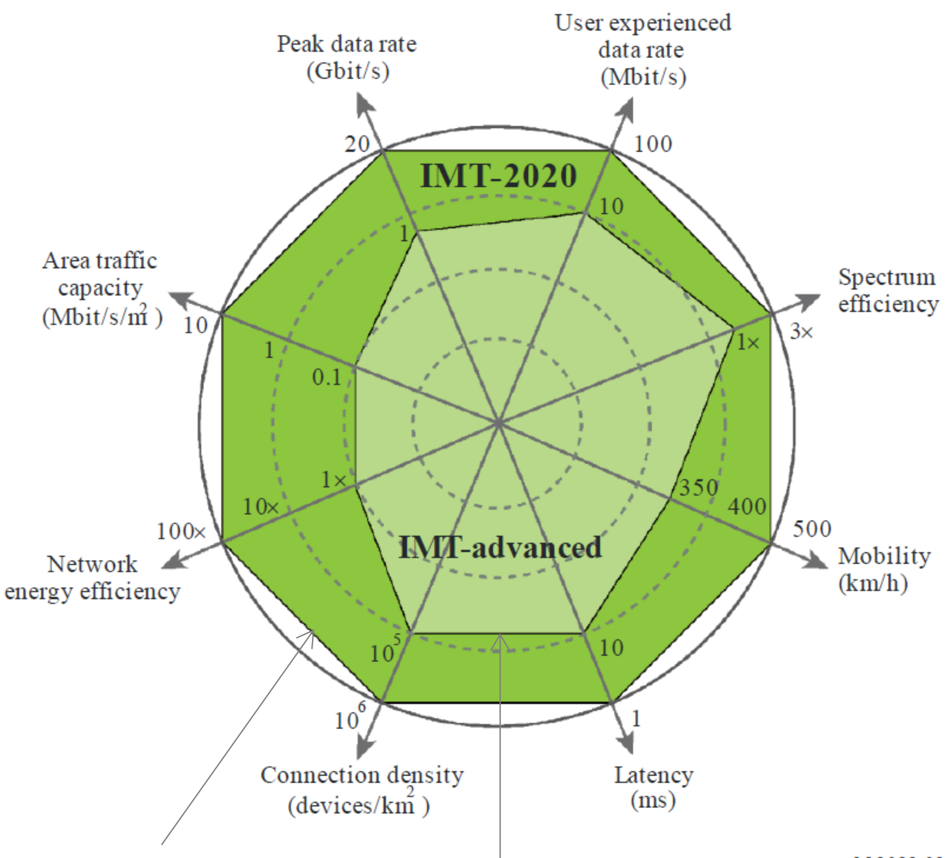
- 5G is the ITU's IMT-2020 initiative, standardised by 3GPP, which offers substantial advancements over 4G (see across)
- Notably, it offers higher data rates, higher device densities and lower latency, enhancing efficiency with improved architecture and automation, thus lowering the 'cost per bit'
- 5G enables new use cases, in particular relating to enterprises and verticals – through network slicing and improved resilience and security
- Building on 4G's foundation, 5G shares the same core radio technologies (multiple access, modulation and coding techniques)
  - It therefore facilitates a more rapid and seamless transition from 4G to 5G than 4G did from 3G

Key 5G technology enablers include:

- Wider bandwidths (particularly in the new 6 GHz and mmWave bands), which is more efficient spectrally and from a cost perspective (see later slides)
- Faster modulation, beamforming and MIMO
  - MIMO stands for 'multiple input / multiple output' antennas[1]
  - Higher orders of MIMO (more inputs/outputs) increase the throughput in Mbps per MHz of spectrum (see later slides)
  - 'Massive MIMO' can also lead to improved coverage[2]
- Distributed functionality (in the core and radio networks)

5G comes in a number of flavours, including 5G NSA, 5G SA and 5G advanced (discussed next)

Evolution from LTE-Advanced (4G) to IMT 2020 (5G)
[ITU-R Rec IMT-202 M.2083-0 Fig.3]



5G requirements specified by the ITU

4G requirements defined by the ITU are represented by the edge of the light-green area in the spider diagram

[1] For example, MIMO 4x4 (or '4T4R' for 4 Transmit and 4 Receive antennas)
[2] As discussed in later slides, beamforming with Massive MIMO allows one to trade off some of the increased capacity for improved coverage, helping higher mid bands behave like lower mid bands from a coverage performance perspective

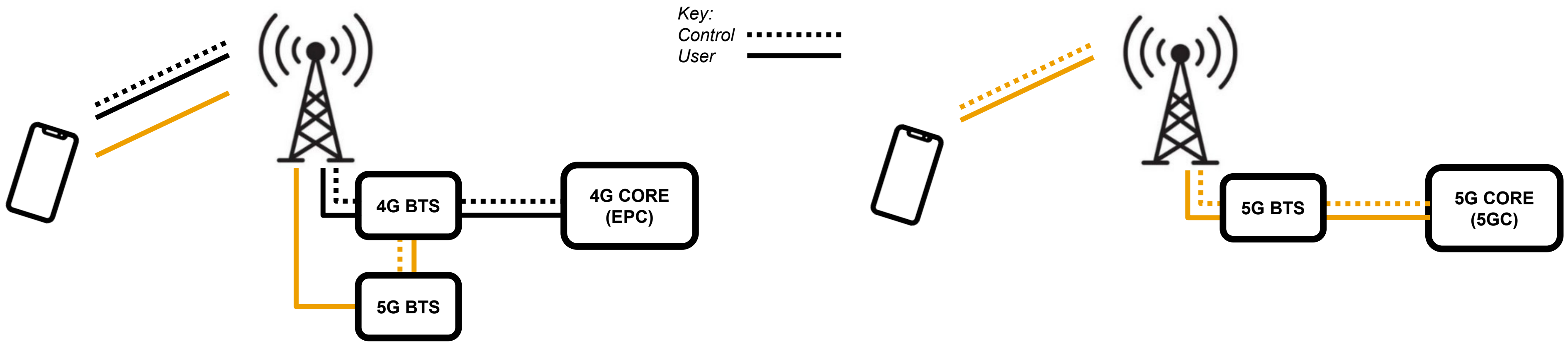
5G Primer for non-specialists: 5G NSA and SA

5G NSA is a stepping stone to 5G SA. Unlike SA, NSA requires a 4G carrier to control the 5G transmission.

Delivery of 5G to end-users within NSA and SA deployment modes

Non-standalone 5G architecture (NSA)

Standalone 5G architecture (SA)



Good for mobile data, but little else

Network slicing, low latency, lower opex

- MNOs have two primary paths for 5G deployment, each with variants within: non-standalone (NSA) and standalone (SA)[1]
- 5G NSA is technically more complex and performance limited, but cheaper as it leverages the existing 4G core network in particular[2]
- Conversely, SA deployments rely on the new 5G core network (5GC) to deliver full end-to-end 5G connectivity and realise 5G's full potential. This requires a completely new architecture and additional operational expertise which requires investment
- In NSA, 5G is 'anchored' to 4G, i.e. the 4G network *manages* the 5G base station (BTS) – hence the network must provision both 4G and 5G radio resources for 5G service delivery, which is why NSA is limited in its potential
  - NSA cannot achieve the low latency (needed for a class IoT use cases) or the full potential of network slicing that 5G offers (see next slide), while also requiring more energy run the network (since both 4G and 5G carriers are needed to maintain a 5G session)
  - 5G NSA essentially acts as a transitionary capacity extension to an existing 4G network –fine for eMBB[3], but little else
- Many initial 5G deployments favoured NSA, allowing MNOs to quickly deploy 5G services whilst avoiding the cost and complexity of 5GC deployment/ operation – however, with increased 5G adoption, MNOs are shifting towards SA for its full functionality and performance

[1] *Both utilise 5G Radio Access ('5G New Radio' or '5G NR' in short)*
[2] *The 4G 'Enhanced Packet Core (EPC)*

5G Primer for non-specialists: network slicing and other use cases

5G SA is required to achieve the full benefits of network slicing – and thus to fully address the private networks and enterprise segments.

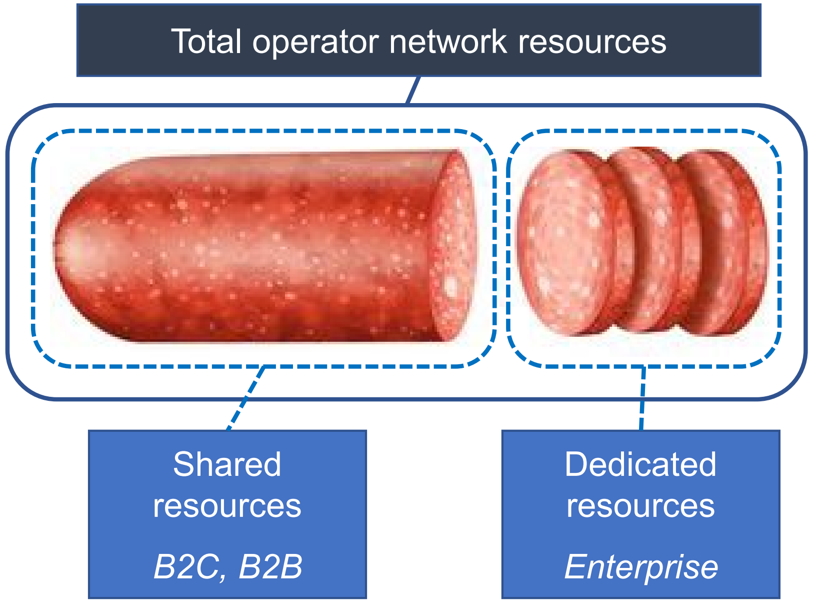
Network slicing

- Network slicing enables resources on a public 5G network to be dedicated to a specific enterprise, forming a distinct, end-to-end private virtual network
  - A private network may use one or more of these dedicated 'time-slices', amounting to a fixed % of network resources[1]
- This offers data isolation and privacy, and facilitates SLA[2] definition covering data speeds, latency, network availability, etc.
- Whilst possible with 5G NSA, this imposes material constraints: SA is key to realising the full potential of network slicing

In short, it is harder for operators to properly address the private networks and enterprise segments without 5G SA.

Other use cases for network slicing and/or 5G SA include:

- Applications requiring low latencies and high network availability:
  - Transport: connected vehicles, fleets and infrastructure
  - eHealth: remote supervision and reaction
  - Manufacturing: automation, JIT supply
  - Energy: autonomous grid
  - Public Safety: rich multi-media comms
  - Transport/ Railways: basis of replacement for GSM-R
- Note: other applications such as less time-sensitive IoT applications, connected staff and assets (e.g. in Hospitality) may also be addressed with 5G NSA



Shared resources (B2C, B2B):
- No Quality of Service guarantee
- Lower prices for access to shared resource

Dedicated resources (Enterprise):
- Network slices with SLA[2]
- Dedicated resources enable QoS guarantee[3]

[1] *A time slice of 1 in N data slots represents 1/N of available network resources.*
[2] *SLA: Service Level Agreements, relating to specific service attributes (e.g. 99.99% network availability, etc)*
[3] *QoS: Quality of Service –metrics related to SLAs*

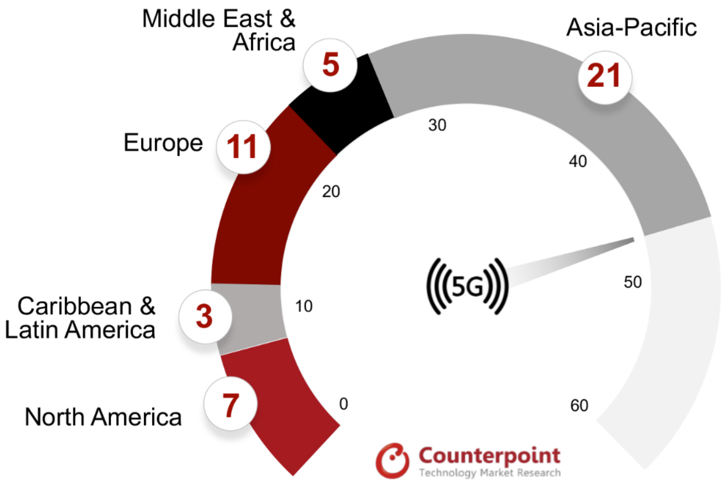
Current 5G SA deployments worldwide

47 operators deployed 5G SA commercially by mid 2023, with many more in the testing and trial phase[1].

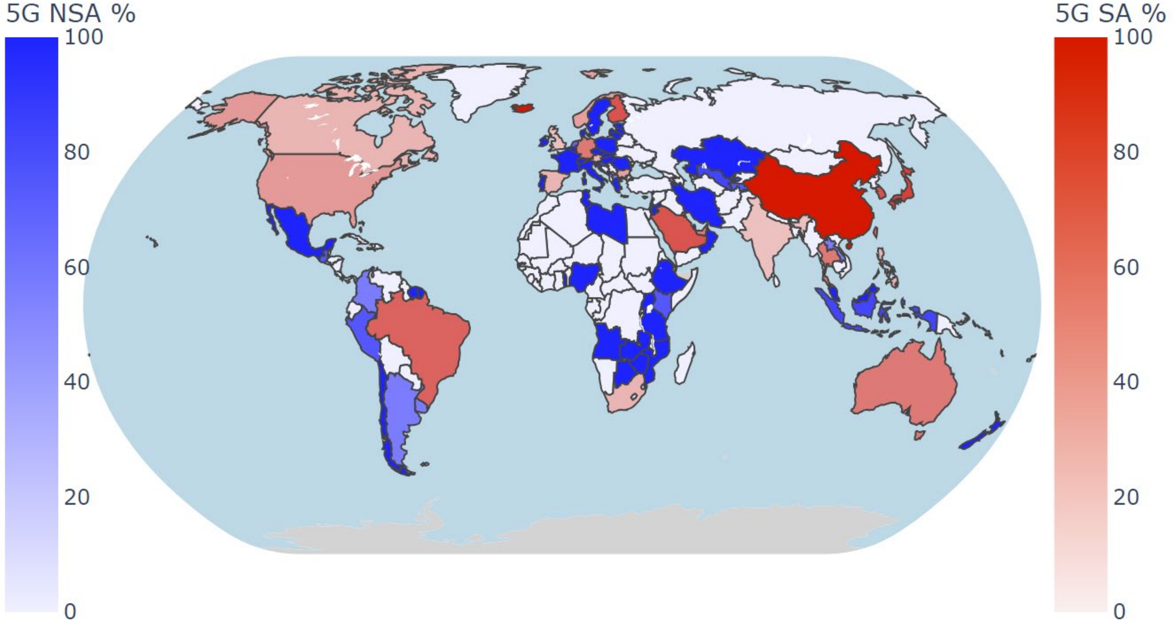
As of mid 2023, the Asia-Pacific region is leading the world in terms of 5G SA deployments[1]

- Most of the 5G SA commercial deployments so far have been in developed economies
- Counterpoint Research expects that the next bulk of network rollouts will take place in emerging markets, driving the continuing transition from 5G NSA to 5G SA

Number of 5G SA deployments by region, H1 2023[1]



Proportion of 5G SA versus NSA deployments, September 2023[2]



[1] Research and graphic from Counterpoint Research.(counterpointresearch.com)
[2] Research and graphic from STL Partners (stlpartners.com)

5G Advanced

5G Advanced includes a range of enhancements that require SA deployment to fully exploit.

5G Advanced: a stepping-stone to 6G

- 5G Advanced addresses a diverse range of items that further improve 5G network optimisation, management and efficiency (through, amongst other things, with introduction of AI and machine learning) as well as 5G performance (positioning and relay/ coverage extension developments, for example)
- It also includes enhancements for specific use cases (including smart production and productivity, for example)
- As such, 5G Advanced contains key technology components that form precursors to essential elements of 6G

5G Advanced Flagship Features

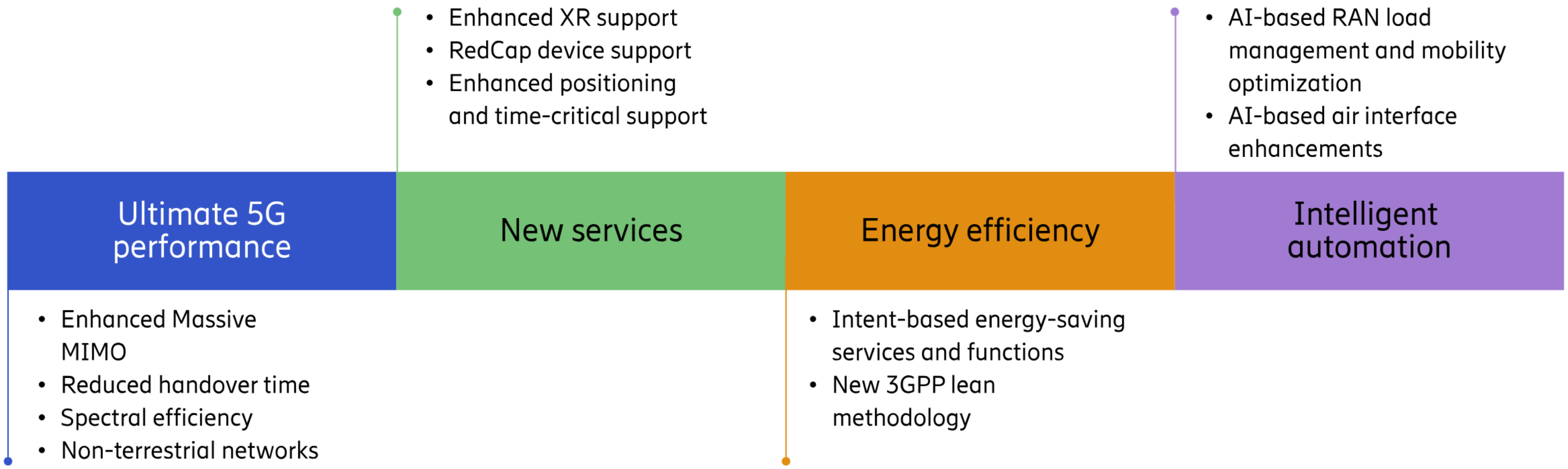


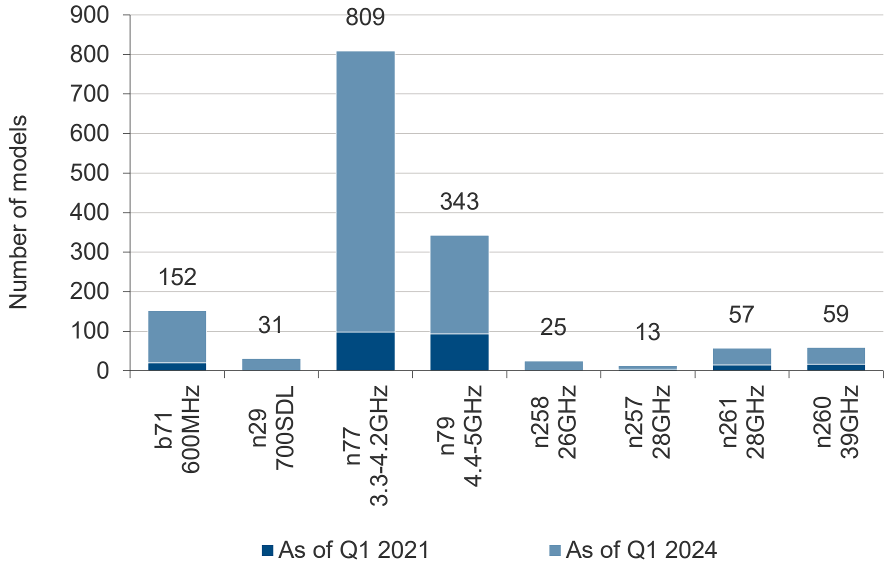
Image courtesy of Ericsson

Device ecosystem

Band support within individual devices is fast becoming a non-issue.

The number of 5G smartphones supporting key new bands has risen sharply between 2021 and Q1 2024[1]

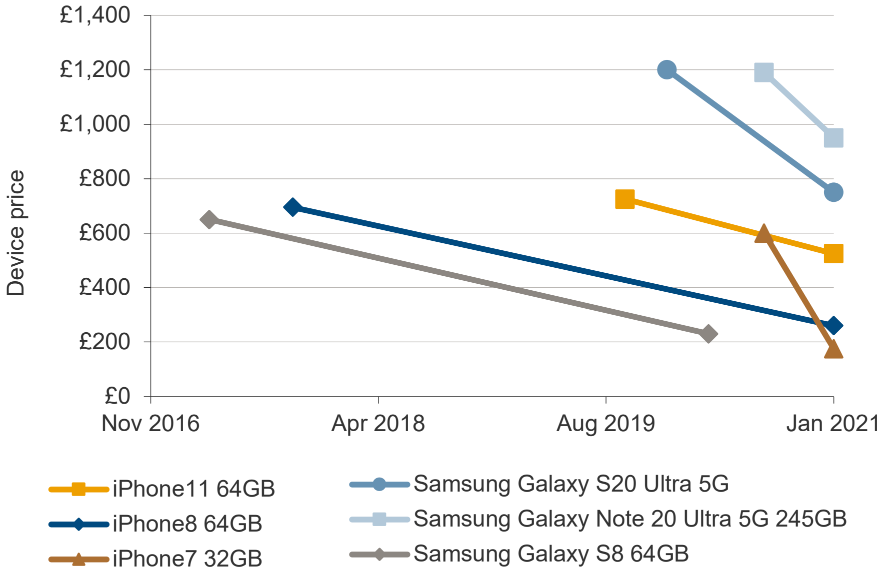
Smartphone band support Q1 2024 versus Q1 2021



- While the number of available frequency bands has increased significantly with each successive generation of mobile technology, band support within devices is fast becoming a non-issue
- Leading smartphones with all of the above sub-6 GHz bands plus at least 3 of the microwave bands include the Apple iPhone 14 and 15 series, Google Pixel 8 (GKWS6) and Asus Qualcomm EXP21
- Given their form factor, it is easier to include antennas to support new bands and higher order MIMO in FWA devices, hence these are likely to be available and diffused even faster

The price of compatible devices is invariably an important factor influencing the rate of adoption of new mobile technologies

Historic price evolution for a sample of Smartphones (pricespy.co.uk)



- Prices of new devices tend to drop rapidly after launch (see above), with the high-end devices of today quickly joining the mid-range devices of tomorrow – and the rate of price erosion is accelerating
- Secondary markets also yield cheaper entry-points for consumers
- These trends support the global diffusion of 5G smartphones with ever-increasing band support

5G adoption is far more rapid than it was for 4G: it took 4G five years from launch to reach 500m global smartphones – while 5G exceeded 1.5 billion within its first 5 years (2023)[2]

[1] Source: Coleago analysis based on GSA data
[2] Based on Ericsson data

Increasing the efficiency of spectrum use (1)

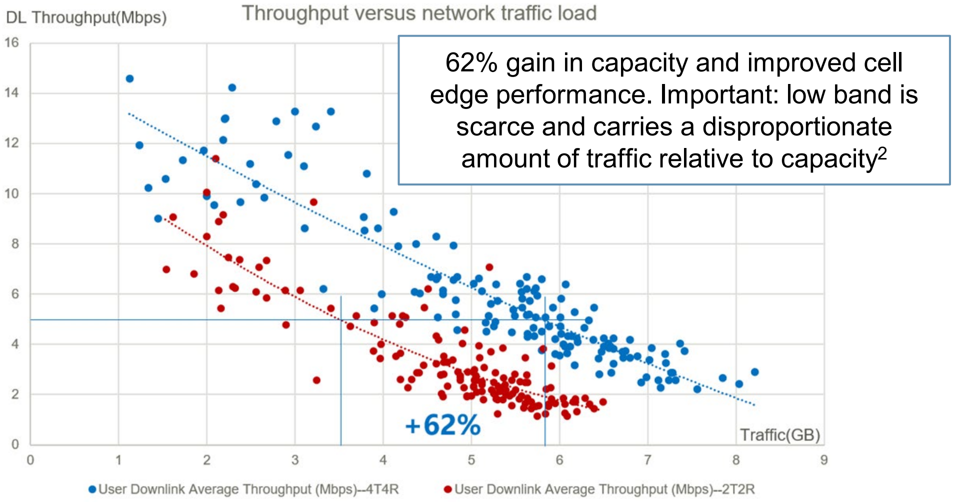
The 3.5 GHz band accounts for around a third of current bandwidth, but with 64x64 MIMO, it could already deliver over 60% of capacity between 700 MHz and 3.8 GHz.

Massive MIMO also allows the trading-off of some of the extra capacity for improved coverage in metro areas – allowing higher mid bands to behave like lower mid bands.

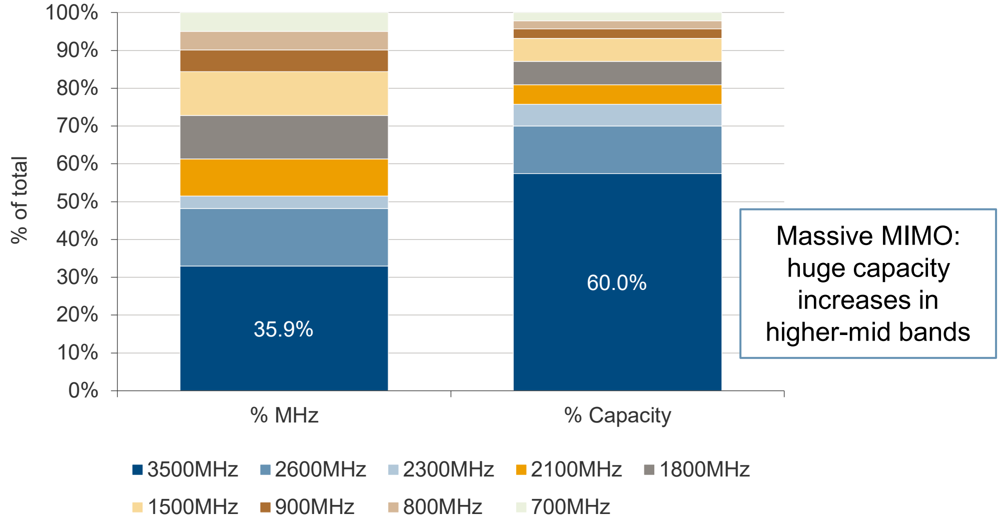
Increased sectorisation and higher order MIMO[1] drive higher data throughputs (in Mbit/s per MHz per site)

- Adding a 4th sector to a 3-sector site may extend the effective site capacity from a given band by around 40%
- Conservative rule of thumb: each doubling of the MIMO order above 4x4 MIMO (4T4R) increases capacity by 1.3x
  - For example, 64x64 order MIMO ('massive MIMO') can generate over 3.3x more capacity per MHz than 2x2 MIMO
- More optimistic views (e.g. Huawei): 32x32 MIMO in FDD yields 5x the throughput of 2x2 MIMO – 64x64 MIMO in TDD yields 3.7x the throughput of 8x8 MIMO
- Because of the size of low band antennas, increased sectorisation and high-order MIMO is easier to implement in mid-to-high bands
  - 4x4 MIMO available in sub-1GHz (8x8 will be standard in 2025)

Commercial LTE 900 MHz: 4x4 MIMO versus 2x2 MIMO (Huawei)

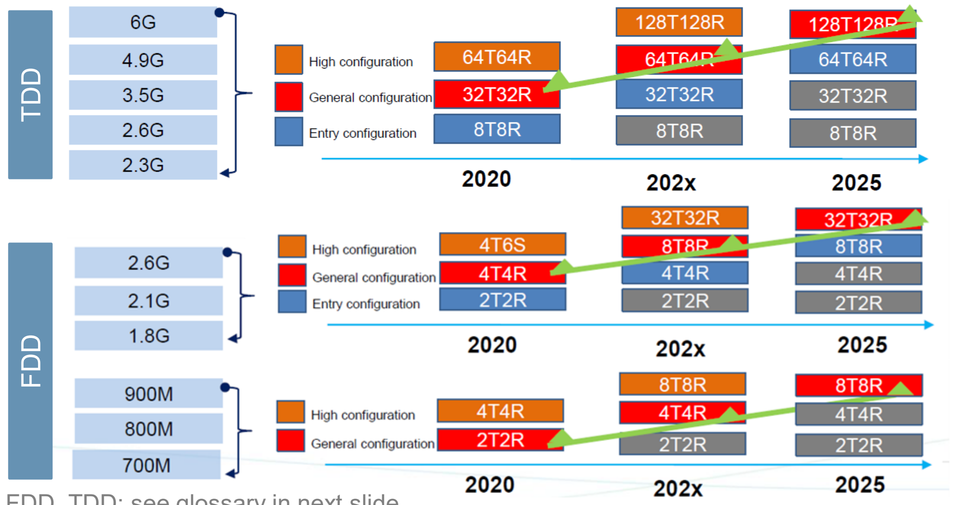


Relative bandwidth and capacity by band (with MIMO 64x at 3.5GHz)



Huawei MIMO evolution roadmap

Launch of '128T Meta Massive MIMO' announced by Huawei at MWC24[3]



FDD, TDD: see glossary in next slide

[1] MIMO: see 5G Primer (earlier slide) for an explanation. [2] Tutela (2020) suggests low bands carried ~30% of all 4G traffic in a sample of 5 EU markets, despite accounting for a small % of total deployed 4G capacity. We assume 10-20% of all urban data traffic globally (see Chapter 5). [3] 21 February 2024: Huawei claims a doubling of spectral efficiency to 12+Gbps capacity, with +5dB coverage gain.

Increasing the efficiency of spectrum use (2)

Wider logical channels yield better speed performance, if not capacity per MHz.

Creating wider logical channels with carrier aggregation (CA)

Example: CA over three bands

Frequency	Total bandwidth	Max downlink data rate[1]	Delivered data rate (RF path)
900 MHz	2x10 MHz	100Mbit/s	90Mbit/s
1800 MHz	2x20 MHz	200Mbit/s	170Mbit/s
3500 MHz	50 MHz	300Mbit/s	300Mbit/s
Total delivered data rate to the handset/device			560Mbit/s

In this example: 560Mbps delivered with CA versus 300Mbps if 'camped' on 3500 MHz without CA, or 90Mbps if camped on 900 MHz

- The delivered data rate to the device is less than the maximum for FDD spectrum, due to propagation changes across the cell
- For TDD, the delivered rate is the same as the maximum, because TDD either works perfectly or not at all
- The resulting performance benefits require no additional to RAN infrastructure, albeit there is an incremental cost of CA software within each cell-site or baseband site
- Note that CA only benefits speed performance in available bands: CA does not increase total capacity, nor improve coverage

Glossary:

- ***UL**, **DL**: Up/Downlink; **RF**: Radio Frequency (path, channel, radio unit); UE: User Equipment; BS: Base Station*
- ***FDD**: Frequency Division Duplex, used in all lower bands ('paired spectrum', with one equal part of the band used for UL, the other for DL)*
- ***TDD**: Time Division Duplex, used in 2300 MHz, at least part of 2600 MHz and all higher bands ('unpaired', using different timeslots for UL and DL and allowing flexible allocation of bandwidth to each –which is far more efficient)*

wide band deployments are more efficient than CA

- Notwithstanding the benefits of CA, it is still better to deploy wider RF channels across larger chunks of contiguous spectrum in fewer bands
- Combining a higher number of narrow RF channels (yielding the same total MHz) but relying more heavily on CA, is less efficient
- For example, aggregating separate blocks (narrow channels) of spectrum in the same band would lead to loss in total capacity per MHz due to Band-Edge-Mask (BEM) filter restrictions

wide band deployment versus CA (example)

	100 MHz	50 + 50 MHz
Complexity	Single carrier	Needs intra-band CA
Channel utilisation	98.3%	95.8%
Physical layer signalling	6.3% overhead	Approx. 12% overhead
Physical layer configuration	A single 100 MHz carrier offers more flexibility than 2x50 MHz carriers to configure sub-bands within the carrier	
Carrier activation / deactivation delay	2ms	10ms
BS implementation	Requires one radio unit only	May need two radio units
Spectrum management	Guard bands may be required if networks are unsynchronised	Two additional guard bands if networks are unsynchronised
UL support	No CA required in the UL	Uplink CA may not be supported by all UEs
UE consumption		30mA additional power consumption for the second CC (50-90% RF power increase over the non-CA case)

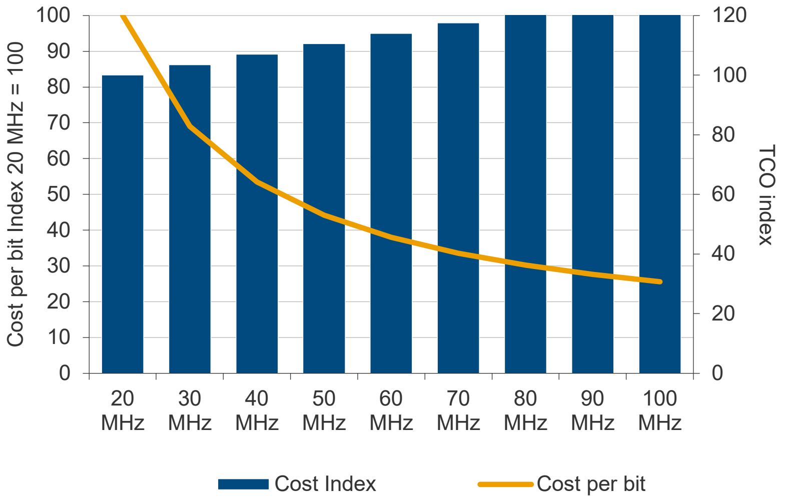
[1] Assuming a gross throughput of 10Mbps per MHz. In FDD mode half the bandwidth is available for downlink (DL) and half for uplink (UL). For TDD (used for 3500 MHz), we assume a DL/UL ratio of 4:1 (DDDSU scheme) meaning that 3 out of 5 timeslots are allocated to DL.

Increasing the efficiency of spectrum use (3)

It is also far more cost-effective to deploy wide band channels than to rely on CA, especially when massive MIMO is used.

Allocation of up to 100 MHz per operator in one band

Cost per bit depending on channel bandwidth (up to 100 MHz today)

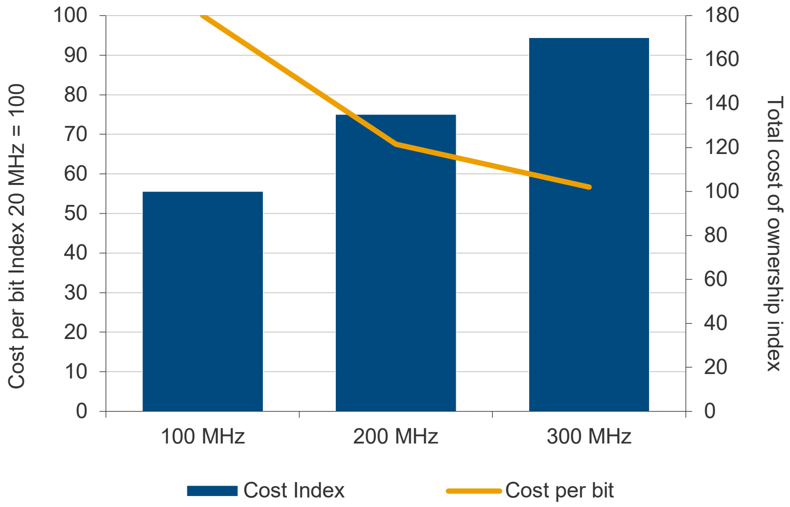


- From a network cost perspective, the wider the channel that is deployed in a single radio, the lower the cost per MHz deployed, and therefore implicitly the cost per bit
- Deploying technology enhancements such as sectorisation and higher-order MIMO is also much more cost effective over wider allocations – as the cost of these enhancements is broadly the same, whether the channel is narrow or wide
- A 100 MHz deployment in a single band yields a cost per bit that is around a quarter of that for a 20 MHz deployment

While 3GPP standards currently provide for channels up to 100 MHz wide, they allow up to 400 MHz in carrier aggregation mode

Allocations of more than 100 MHz per operator in one band

Cost per bit with per operator allocation of more than 100 MHz



- Equipment suppliers' efforts aim at allowing their 5G radios, including those implementing massive MIMO and beamforming, to operate with the widest possible channel bandwidth ('instantaneous bandwidth') and to make that 'tuneable' in the widest possible frequency range ('operating bandwidth'
- 5G radios that are now deployed in 3400-3800 MHz band are starting to operate at an 'instantaneous bandwidth' of 100 MHz within a 400 MHz 'operating bandwidth'
- The ongoing research (e.g. for filters and power amplifiers) will allow larger instantaneous and operating bandwidths by 2025-2030
- If 300 MHz is deployed in a single radio, the cost per MHz deployed is 43% lower compared to a deployment in only 100 MHz

Increasing the efficiency of spectrum use (4)

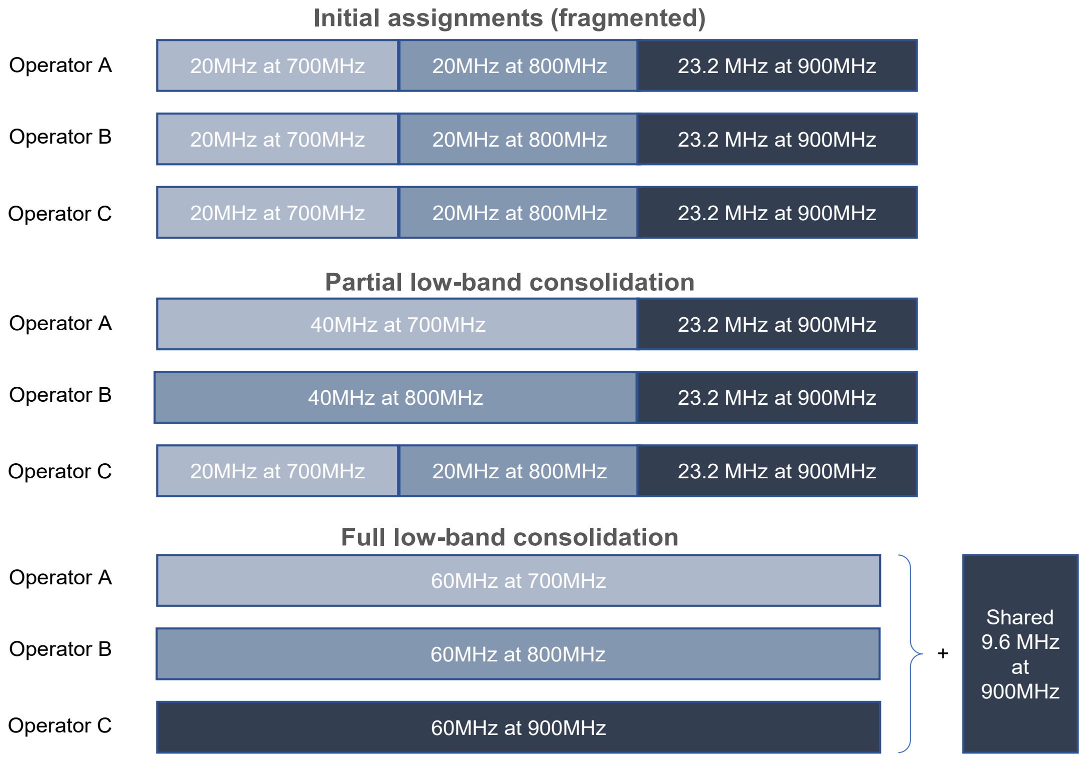
It is far more efficient to deploy wider channels across fewer bands than the opposite.

This is why it is important that policymakers favour wide band allocations and/or encourage spectrum trading and/or pooling.

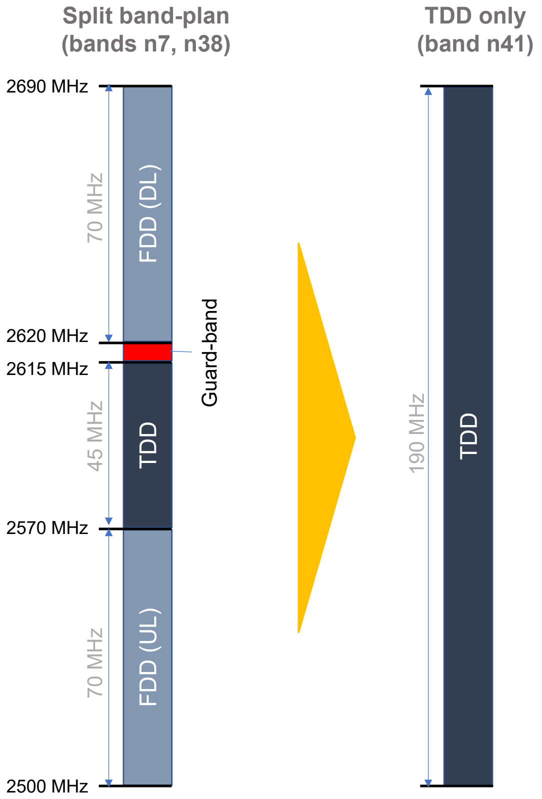
Further measures to drive more efficient use include spectrum consolidation and band-plan reorganisation to TDD

- Spectrum consolidation through multi-lateral trades or spectrum pooling would allow lower cost and higher-performance deployment
- This applies to low bands, in which operators typically hold small amounts in 700 MHz, 800 MHz as well as 900 MHz, but also in mid bands - in 1800 MHz and 2100 MHz for example, which are close substitutes, most operators hold no more than 2 x 20 MHz in either
- Reassigning the 2600 MHz band from a mix of FDD and TDD to TDD-only (as implemented in China, the US, Canada, Saudi Arabia, the UAE, Thailand, Nepal and Kenya) would lead to increased efficiency[1]

low band consolidation in a 3-player market (illustration)



Reassigning 2600 MHz from split FDD/TDD to FDD



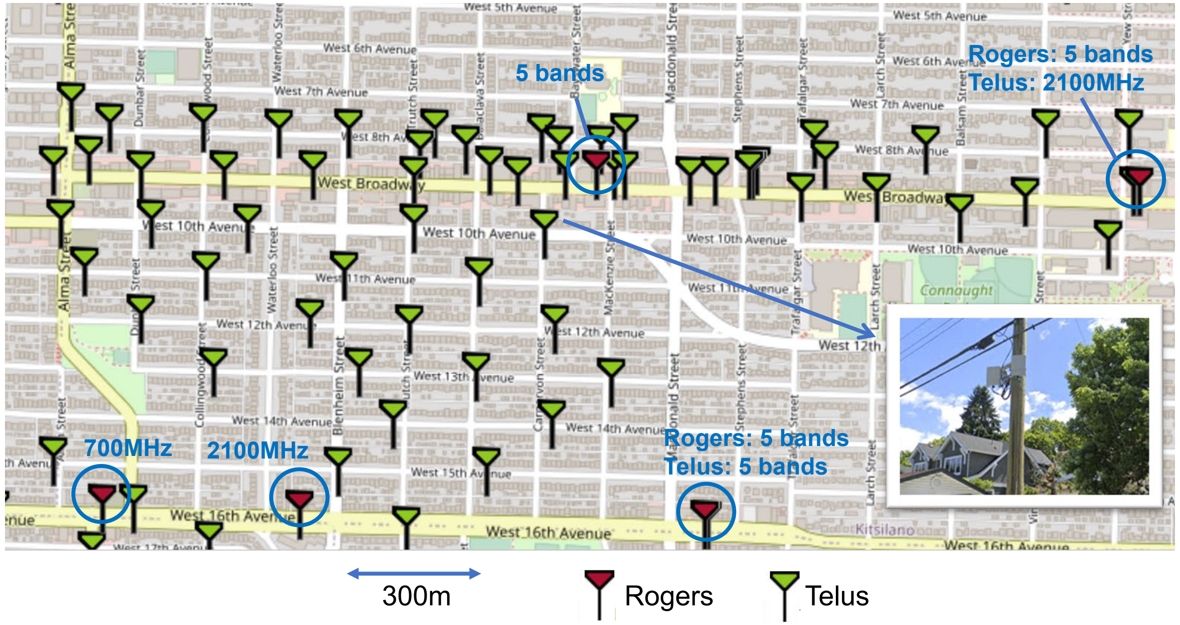
[1] *TDD is more efficient by virtue of allowing a greater proportion of bandwidth to be allocated to downlink traffic. The split band-plan is inefficient because it leads to fragmentation, which limits allocation options, and higher-order MIMO would be more difficult to implement across split TDD and FDD holdings where an operator to have assignments across both portions.*

Evolving shape of networks: macro sites versus small cells

Small cells are increasingly being used in conjunction with a macro layer to provide in-fill coverage and capacity.

Small cells will play an increasing role in network densification – they are already central to operator strategies in North America

Example: Telus versus Rogers networks (Vancouver snapshot, January 2021)



Globally, small cell deployments are likely to accelerate

- In the US, small cells deployments are already over 3x more common than macros (~450k small cells versus ~140k macros end 2022)[1]
- The small cells forum (SCF) estimates that small cell deployments grew by 15% worldwide between 2021 and 2022, and forecasts[2]:
  - A global installed base reaching 10 million small cells by 2031
  - Massive Indian deployments, with a 24% CAGR in enterprise markets and 26% in public (urban and rural)
  - South Asia accounting for 22% of the total installed base of small cells by 2028, the largest regional total, overtaking China's base by end 2025
  - Strong momentum in emerging regions, especially Africa and Latin America, from 2025

- The unit cost per small cell is typically far lower than that for a macro site, but far more small cells are required to deliver capacity across a given area – a combination of macro layers with small cells for in-fill coverage and capacity is becoming a typical network topology
- However, Europe in particular has been lagging in this domain - planning constraints and limited or difficult access to public infrastructure form a major barrier to small cell deployment: lengthy and costly processes diminish the benefits of small cells relative to macro roll-out

Streamlining planning and facilitating access to public real-estate assets for small cell deployments should be a major policy priority (discussed further in Chapter 10)

[1] Source: Benton Institute for broadband & Society, March 2023
[2] Source: The SCF Market forecast report 2023

Opening the radio access network (RAN)

Open RAN will promote greater vendor diversity, inter-operability and agility, hence improved RAN economics and performance.

Commoditising the physical layer will promote vendor and solutions diversity, driving innovation and helping reduce costs

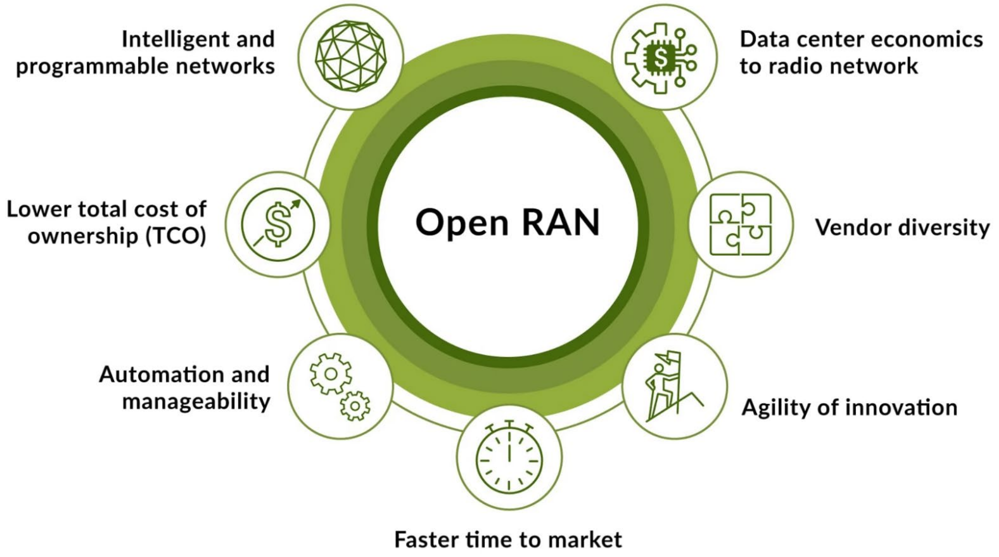
- RAN virtualisation involves migrating 4G core from the ‘physical domain’ to the 5G ‘virtual domain’
- Vendor-agnostic, interoperable components may allow more upgrades without replacing hardware[1]
- Reduced entry barriers to alternative providers in each domain will further help reduce costs by promoting competition
- Greater access to best-in-class providers in each field will drive innovation

Two competing approaches: the 3GPP versus the ‘O-RAN Alliance’ approach

- The ‘O-RAN Alliance’ supports a wider range of functions and interfaces than 3GPP
- The greater the number of open interfaces, the greater the potential to diversify vendors and achieve cost benefits
- But more open interfaces also means more potential vulnerabilities that need to be addressed

Hence while the 3GPP approach is less far reaching, it may raise fewer security concerns

Key prospective benefits of Open RAN



[1] Source: Vodafone website. Vodafone refers in particular to upgrades to upgrades to orchestration, management and automation software
[2] Image courtesy of Juniper Networks.

Interoperation with LEO satellite communications (1)

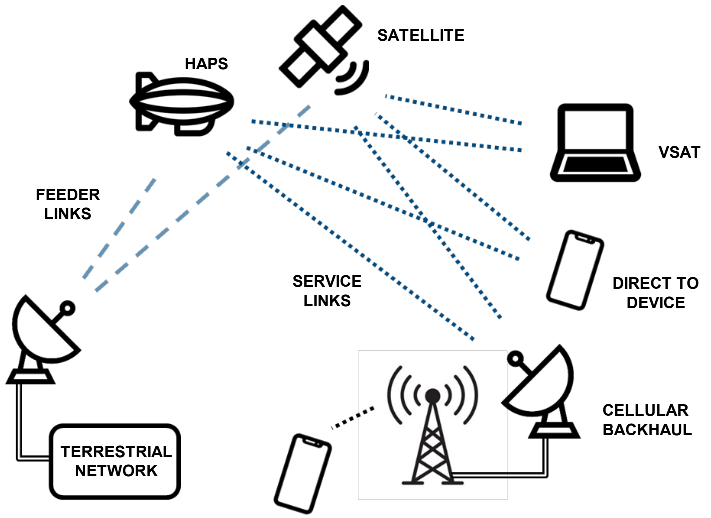
Non-terrestrial networks (NTN) seamlessly integrate into 5G, with the focus being on 'direct To device' services, initially for voice and messaging.

NTN prioritises service continuity and ubiquity, essential for bridging the rural coverage gap.

Two distinct spectrum approaches are employed, each offering unique advantages and limitations.

Non-Terrestrial Network (NTN) fundamentals

Examples of NTN connectivity



- NTNs function above the surface of the earth, with the industry's focus being satellite systems; NTN connectivity covers cellular backhaul and VSAT, however significant attention is directed towards 'direct to device' (D2D) solutions
- Standardised within 3GPP, NTN is fully integrated into the 5G network; despite greater latency, due to the distances involved, NTN prioritises extending 5G coverage and reach to deliver service continuity and ubiquity – however, it cannot compete with terrestrial data rates, but complements them, targeting 1Mbps data rates for pedestrian handhelds
- The first iteration of standardisation was completed in 2022, and work has moved onto enhancements and optimisations (such as additional spectrum bands and multinational coverage)

NTN spectrum

Two spectrum options are being proposed/ used for NTN

RE-USE OF TERRESTRIAL BANDS	SPECIFIC SATELLITE BANDS
• Reuse of an individual MNOs existing terrestrial allocations • Typically involving bands below 1GHz or at 2100 MHz (note: these will require FDD modulation[1]) • Requires coordination with terrestrial networks to limit interference potential	• Use of two existing mobile satellite service bands – at 1.6GHz and 2.1GHz) • These bands have specific designations within the 3GPP standards (as n255 and n256) • Bands at Ka- and Ku-band are expected to follow[2]

- Re-using an existing MNO's spectrum offers immediate benefits as the bands are already part of the 5G ecosystem and compatible with existing (5G) handsets
  - This will bring truly global coverage to billions of handsets
  - Unlike solutions such SpaceX's Starlink, which requires dedicated terminals
- Although specific (dedicated) satellite bands are generally globally allocated, they tend also to be limited in bandwidth[3] – a further constraint on NTN deployments (over and above incompatibility with existing terrestrial mobile devices)
- However, careful coordination is needed to mitigate interference within the MNO's spectrum and neighbouring MNOs' bands; cross-border interference also presents a risk, potentially leading to service gaps immediately within a country's borders

[1] FDD (Frequency Division Duplex) uses dedicated frequency ranges for uplink and downlink traffic, unlike TDD (Time Division Duplex). TDD is common for bands above 2100 MHz but is not technically feasible for NTN-mobile communications.
[2] Ku band: 12-18GHz; Ka: 26.5-40GHz [3] Particularly in the lower Satellite bands such as n255 and n256

Interoperation with LEO satellite communications (2)

Re-using terrestrial IMT bands for D2D LEO satellite comms will bring truly global coverage to billions of smartphones.

D2D LEO is a natural extension of the use of satellite links to provide backhaul to remote sites - recent developments include:

- Rogers Wireless and LEO operator Lynk announced a first LEO-mobile D2D call in December 2024 (to a Samsung Galaxy S22 smartphone) – a commercial Satellite service to extend Rogers' coverage to rural Canada using its own spectrum is planned for 2024[1]
- At the 10th Latam Spectrum Management Conference in February 2024, Lynk claimed to have signed MSAs signed with 35+ operators, covering around 50 countries, with active commercial beta services in 7 markets
- SpaceMobile and OmniSpace are working in the 1-3 GHz band to provide voice, SMS and data services of up to 30Mbps directly to unmodified cellular equipment, with Omnispace due to test direct-to-smartphone LEO plans with MTN in Africa[2]
- On 14 March 2024, the FCC adopted a framework to allow Satellite-to-Smartphone coverage in remote areas in the US
- Over half the agenda points for WRC27 relate to satellite, underscoring the importance of the LEO revolution

China Mobile launches the world's first 6G test satellite[3]

Networks including tens of thousands of LEOs, each covering areas with a radius of ~20-50Km, will allow continuous coverage of the bulk of the Earth's surface, while keeping latency in check

[1] Source: MobileWorldLive.com, 15 December 2023. [2] Source: Spacenews.com, 13 and 18 March 2024. Note Amazon's Project Kuiper will offer TN-like 5G services through its cellular base station terminal with speeds between 100Mbps and 16Gbps for cellular devices at specific locations, albeit this will require dedicated terminals. [3] Image and headline courtesy of China Daily, 5 February 2024.

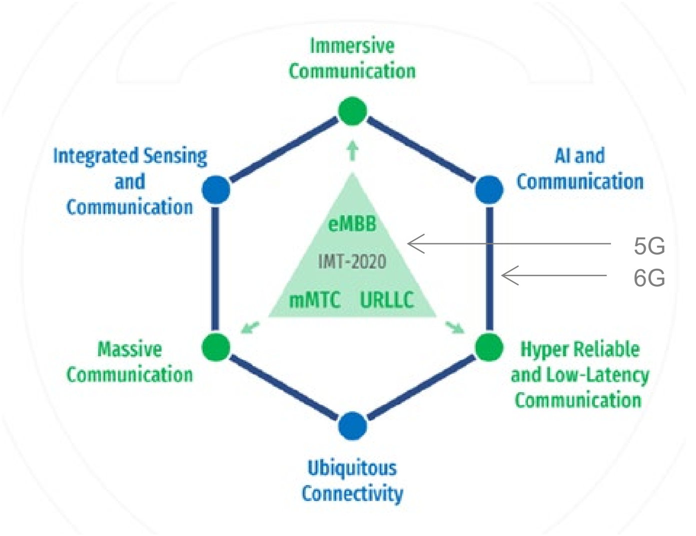
Outlook for 2030: 6G

The ambitions of 6G follow the megatrends towards immersive communications and hyperconnectivity in particular.

As currently envisaged, 6G represent a far bigger leap than from 4G to 5G

- 6G is in its early stages of development: the ITU recently agreed its framework and overall objectives for IMT-2030[1] (the ITU's name for 6G)
- As with 4G[2] and 5G[3], this paves the way for the development of new radio technologies by vendors and standardisation bodies
- 6G seeks to build on the foundations of 5G to:
  - Extend 5G's enhanced mobile broadband, which enables delivery of faster services, such as HD video, whilst on the move, into immersive communication providing an interactive/ immersive video experience
  - Strengthen 5G's ultra-reliable and low-latency communication (URLLC) with stricter requirements around reliability and latency, extending the scope of IoT devices and applications
  - Enable integrated multi-dimensional sensing combined with high-precision positioning to improve assisted navigation
  - Provide ubiquitous connectivity, especially in underserved areas
  - Integrate AI and Communications for applications such as intelligent network management, predictive analytics, and personalised services
  - Enhance intelligent industrial applications including telemedicine and the management of energy and power grids
- To support these usage scenarios, 6G will improve upon 5G's capabilities (which can be seen in the earlier radar plot comparing 4G and 5G) – these capabilities are, however, estimates, pending further research
- While 6G would utillise existing IMT spectrum, additional bands will be necessary in the cm-range (7-15GHz) and the sub-THz range (100-300GHz or higher)
- Such high frequencies will be accompanied by propagation constraints, requiring innovative solutions to overcome these and deliver the massive leap in performance

6G (IMT-2030) Usage Scenarios



6G (IMT-2030) Key Capabilities

Capability	Target
Peak data rate	50 – 200 Gbps
User experienced data rate	300 – 500 Mbps
Spectrum efficiency	1.5 – 3x greater than 5G
Area traffic capacity	30 – 50 Mbps/m^2
Connection density	10^6 – 10^8 devices/km^2
Mobility	500 – 1,000 km/h
Latency	0.1 – 1ms
Reliability (air interface)	10^{-5} – 10^{-7}
Positioning	1 – 10 cm

[1] *ITU-R Recommendation M.2160*
[2] *ITU-R Recommendation M.1645*
[3] *ITU-R Recommendation M.2083*

3

Implications for stakeholders

Calls to action for operators and public policy makers

The growth in capacity needed by 2030 presents major challenges

From Chapter 1: as much as 3-7x current capacity is needed to meet the traffic growth across different regions, and 7-14x current levels to consistently deliver a 100Mbps data speed experience.

To meet the 2030 demand for capacity, operators will need to:

Acquire and deploy far more spectrum, and re-farm legacy spectrum to 5G[1]

- Need low band for coverage quality and to improve cell edge performance
- Higher bands for capacity

***And* deploy technology enhancements**

- Sectorisation: extra capacity
- Massive MIMO: boost capacity and overall network performance

***And* roll out many more sites**

- Macro sites (albeit densification may be difficult in urban areas), micro sites and small cells

Big issue: higher mid bands (3.4GHz and above) and mmWaves are 5G only, so these do not address the need in certain markets for significantly more 4G capacity between 2023 and 2030[2]

- In the absence of (significant) extra 4G spectrum, operators in those markets with further legacy-traffic growth need to densify the network and deploy technology enhancements, *just for 4G*
- The good news is that these will not become stranded 4G-only assets[3]: new radio equipment and MIMO antenna systems offer a smooth upgrade path to 5G (via software upgrade)
- Therefore, near-term deployments for 4G will also support future 5G capacity requirements: the extra sites and massive MIMO will in any case still be needed

Note: issues relating to the transition to 5G and readying networks for 6G are discussed further in Chapter 6

[1] Albeit sufficient legacy bandwidth needs to be maintained to support legacy devices. [2] Globally: 36% rise 4G capacity need until peak in 2027, as discussed in previous slides. [3] Unlike 3G investments in the past, which did not offer a smooth transition to 4G.

New spectrum will be the main source of new capacity

Macro densification may not be feasible in dense urban areas due to lack of site options as well as minimum inter-site distance constraints.

Illustration: route to capacity expansion (3 steps) in 'dense urban' areas, assuming no macro densification[1]

Total MHz (all MNOs)	Baseline	Step 1	Step 2	Step 3
Low band	190	190	190	190
Lower mid band	460	460	**560**	560
Higher mid band	200	**400**	400	**1,100**
Capacity index	100 (A)	142	153	299 (B)

Impact of Additional spectrum

< +100 MHz at 2.3GHz (if not yet allocated)

< +200 MHz 3.6-3.8GHz, +700 MHz in U6G[2]

< Up to **3x** increase in capacity vs (A)

MIMO order	Baseline	Step 1	Step 2	Step 3
Low band	2x	2x	2x	2x
Lower mid band	4x	**8x**	8x	8x
Higher mid band (up to)	32x	**64x**	64x	64x
Capacity index	100	171	185	364 (C)

Plus: Doubling of MIMO order in most bands

< + Up to 8x in lower mid band

< + Up to 64x (on average) in higher mid band

< 22% increase from (B) and **3.6x** (A)

Small cells & mmWaves	Baseline	Step 1	Step 2	Step 3
Extra traffic offload	0%	**10%**	**20%**	**35%**
Capacity index	100	188	222	**491** (D)

Plus: More offload to small cells and mmWaves

< 35% increase from (C) and ~**5x** (A)

A 5x increase in capacity would be sufficient for most of dense urban in Western Europe, but more would be needed beyond 2030[3]

- While the capacity expansion path will vary according to current spectrum allocations, extra higher mid band has the biggest impact
- The initial MIMO order deployed in different bands may also differ (as outlined in Chapter 2 however, 128T Meta Massive MIMO is already available and would provide a further step-up)
- More significant small cell densification and mmWave deployment could drive further growth in capacity

[1] *Based on spectral efficiency factors (bits per Hz) applied in Chapter 5 (national spectrum need analysis).* [2] *See Chapter 4 for the current status of key new bands.* [3] *See Chapter 1: in dense urban, a 5x capacity multiple (2030 vs 2023) would be needed in Western Europe to meet TDI growth as well as a 100Mbps speed experience target with 99% probability. Higher multiples apply in other regions..*

Key imperatives for operators and policy makers

Given the challenging context, operators and policy makers alike will need to pursue intelligent strategies to ensure positive outcomes for all stakeholders.

Operators need to focus on total revenues and costs per bit, with a view to earning their cost of capital[1]

Imperative for operators: drive new revenue streams and/or reduce total costs per bit

- Pressure on industry returns combined with huge growth in capacity requirements mean operators need to work hard to optimise their pricing structures, find new revenue streams, and/or reduce total costs per Mbps
- Quality-based pricing, a step-up from pricing based on data-speed caps, would help underpin ARPU in an era of unlimited data plans and would also benefit customers with more stringent needs for bandwidth availability
- New revenue opportunities may be found across enterprise and industry solutions, within the wider IoT value-chain and across mobile digital applications
- On the cost side, measures are needed to contain opex inflation, reduce the cost of passive infrastructure, and increase the capacity per $ spent

Policymakers need to focus on sustainability of the industry and competition[2]

Imperatives for policy makers: focus on actions that support rather than harm mobile development

- Operators urgently need more spectrum to meet the rising demands for mobile network capacity –policy makers should take steps to ensure additional usage-rights are allocated in a timely manner (see Chapters 4, 5 and 9); this includes in particular:
  - low band spectrum for improved indoor and wide area capacity, notably releasing 600 MHz and 700 MHz SDL as and when possible
  - 2.3GHz, 2.6GHz and 3.5GHz bands, if yet to be assigned, and 6GHz when available
- olicymakers should focus on industry sustainability –avoiding actions that impose additional financial pressures on operators (see Chapters 8 and 9)
- Policy makers should take actions that promote network deployment, by easing planning-approval constraints and facilitating access to public real-estate assets (see Chapter 10)

[1] Returns on Invested Capital (ROIC) align with the operators' weighted-average cost of capital (WACC) to ensure business sustainability.
2 policymakers need to tread especially carefully when operators (and market challengers in particular) are earning returns consistently below their risk-adjusted cost of capital, as this threatens the sustainability of business continuity and competition.

Can speed-based mobile data pricing deliver ARPU growth?

Finland suggests speed-based data pricing can deliver revenue upside: service revenues grew by 16% between 2014 and 2021, while they declined in many other European markets.

The historic launch of 4G and 5G did not deliver lasting price premiums

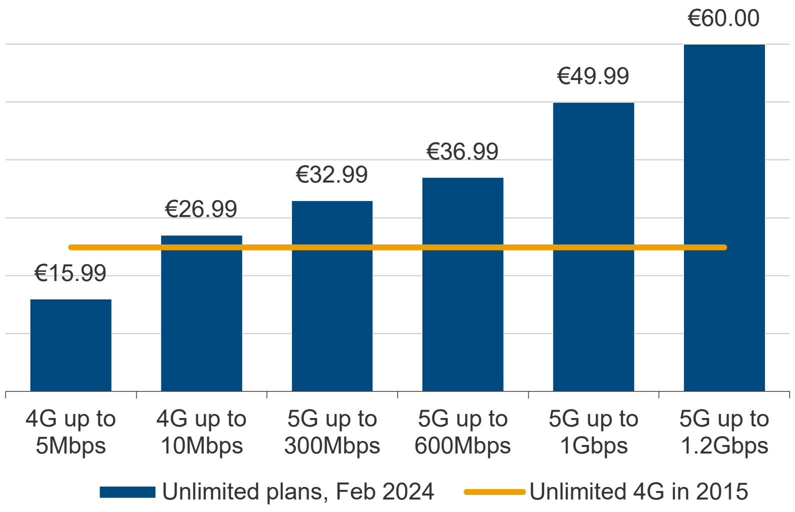
LGU+'s 5G vs 4G pricing in Korea, shortly after 5G launch

	Package Type	5G			4G		
		Tariff KRW	Data pack	Limit after out of pack	Tariff KRW	Data pack	Limit after out of pack
LGU+	Entrance	55,000	9GB	1Mbps	55,900	6.6GB	3Mbps
	Middle	75,000	150GB	5Mbps	74,800	16GB	3Mbps
	High	85,000	Unlimited	Unlimited	88,000	30GB	3Mbps
	Premium	95,000	Unlimited	Unlimited	110,000	40GB	3Mbps

- Maintaining a premium for 5G adoption would be counterproductive: operators have an incentive to drive users to the more efficient technology, allowing rapid re-farming of legacy bands to 5G
- LGU+ soon embedded 5G *discounts* in their plans: customers enjoyed faster speeds with 5G, as well as larger data allowances at lower prices than with 4G
- However, there are possible exceptions: AIS Thailand reports a 10-15% ARPU uplift from 5G customers[1]

Nevertheless, the evolution of prices in Finland does suggest potential revenue upside from speed-based pricing

Elisa Finland pricing



- A standard 4G unlimited plan cost €24.90 per month with Elisa in 2015
- Differentiated speed-based pricing appeared during 2016, starting at €26.90 for up to 50Mbps (a €2 premium)
- All available unlimited plans except the one capped at 5Mbps are now more expensive than the original 4G standard –and both 4G plans include charges for voice and text-messaging (unlike the 5G plans)
- Finland service revenues grew by 16% over 2014-2021, while 7 out of a sample of 11 European markets showed declines over the same period (France, with second-highest growth, increased by 6%)[2]

The issues that prevented a 'technology premium' do not apply to differentiated speed-based pricing *within* a given technology: the Finnish experience points towards more favourable dynamics in this area

[1] *Source: GSMA The Global Mobile Economy 2023.*
[2] *Source: Bank of America Merrill Lynch Global Wireless Matrix, October 2020. The figures include estimates for 2020 and projections for 2021. Note that revenue growth in Finland is unlikely to be attributable to increased FWA adoption: total SIM count only grew by 4% over the period.*

Priority-based pricing offers a further alternative

Combined speed and priority-based pricing could allow operators to better meet the specific needs of individual customers, and to generate revenues that are closer to customers' willingness to pay.

Undifferentiated pricing of data makes little sense for operators and consumers alike

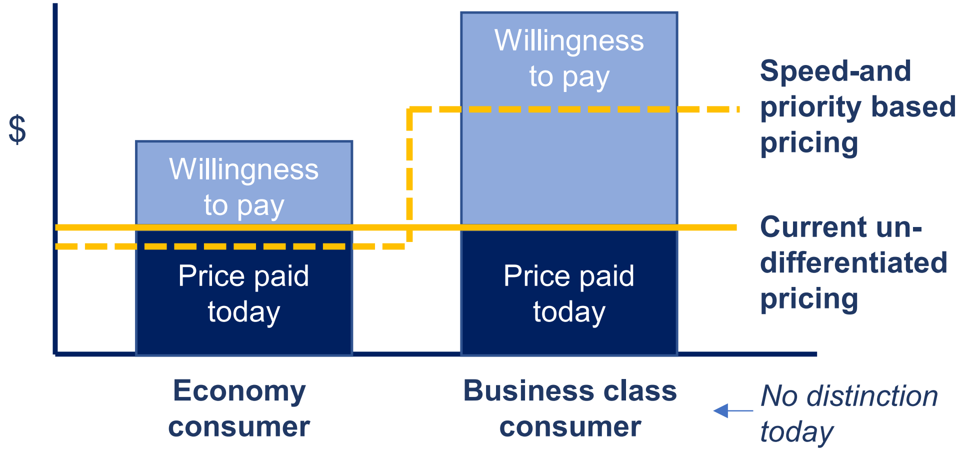
What would happen if Ferraris and Fiat Pandas were sold at the same average price?

- No new Ferraris would be produced, because costs would exceed prices
- The excess demand for Ferraris could not possibly be fulfilled
- Even those willing to pay the true value for a Ferrari could not get one
- Demand for Pandas would be depressed due to their excessive price

Total seller revenues and returns would be reduced and customers would be unhappy

- A fast, reliable bit is more expensive to produce than a slow and unreliable one – and it should be priced accordingly
- Those who *would* pay for extra bandwidth availability are under-served

A tale of two 'Unlimited' customers
(using the same amount of GB per month)



The 10% heaviest users generate 70% of traffic[1] – but with unlimited data, these are unlikely to generate commensurate revenues

- Charging for prioritised access to bandwidth would solve the freeriding problem: those not willing to meet the cost of the bandwidth they consume would adjust their usage, freeing up capacity for those that are
- Operators could offer 'gold', 'silver' and 'best-effort' packages, each with distinct tiered prices –in the event of congestion, 'gold' subscribers would get first call on network resources, much as airline 'gold' or 'platinum' members are always the last to lose their seats if a flight is overbooked[2]

There is evidence from the 2G era of customer willingness to pay for quality and reliability: incumbents with a coverage advantage were able to charge a premium, even though their customers might rarely (if ever) venture outside the footprint of rival operators

[1] *Source: Ericsson Mobility Report, June 2023*
[2] *Note that prioritized access to bandwidth is already offered to Emergency Services/PPDR users in the UK, on EE's public mobile network*

Generating new revenue streams

In addition to optimising pricing structures, opportunities may exist to generate incremental revenue streams across both consumer and business segments.

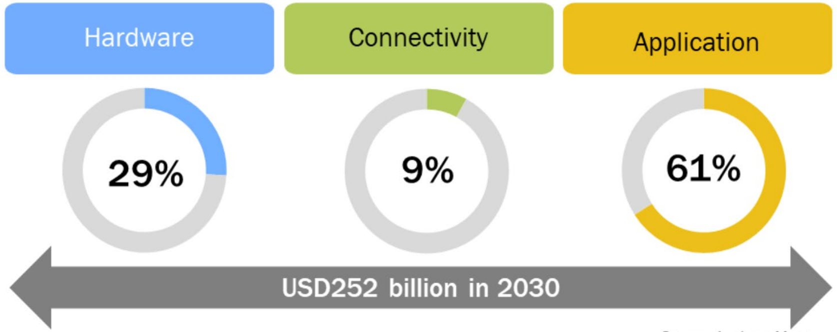
Private networks – underpinning the future Industrial and Enterprise Metaverse

- Network slicing will allow operators to address the private mobile network (PMN) segment cost-effectively (from Chapter 1: ~10% revenue uplift potential)
- However, hybrid solutions involving both slicing and dedicated networks will be needed to support a range of use-cases
- Operators may seek to exploit their relationships, scale and existing competencies to compete in this wider space
- For example, Vodafone and Porsche Engineering claimed in Dec 2022 to have established the first European 5G hybrid PMN at the Nardò Technical Center in Southern Italy

Image courtesy of Nokia

IoT – beyond mobile connectivity

- Analysys Mason projects the global cellular IoT market to reach $250bn by 2030, of which only 9% is attributed to connectivity[1]
- Operators could be well placed to move up the value chain, as few players can assume the burden of telecoms/IoT regulations
- For example, Vodafone pursued global coverage, through partnerships with rival operators including China Mobile and America Movil, providing IoT connectivity in 'some of the most complex regulatory markets' – and a strategic partnership with ARM, which 'removes cost and complexity for OEMs developing connected products, and solutions that deliver high-value business outcomes, such as stolen vehicle tracking and assisted living'
- IoT leadership may also position operators better in the PMN segment



Source: Analysys Mason

Digital services – building on the value of existing customer relationships

- Mobile Fintech successes (covered in Chapter 1) demonstrate the scope for operators to extend customer relationships and drive revenues
- Partnerships with third-parties may allow operators to generate value in other digital categories such as entertainment, gaming, news, health, fitness and education – examples include the Verizon +Play platform as well as its strategic partnership with Meta[2]

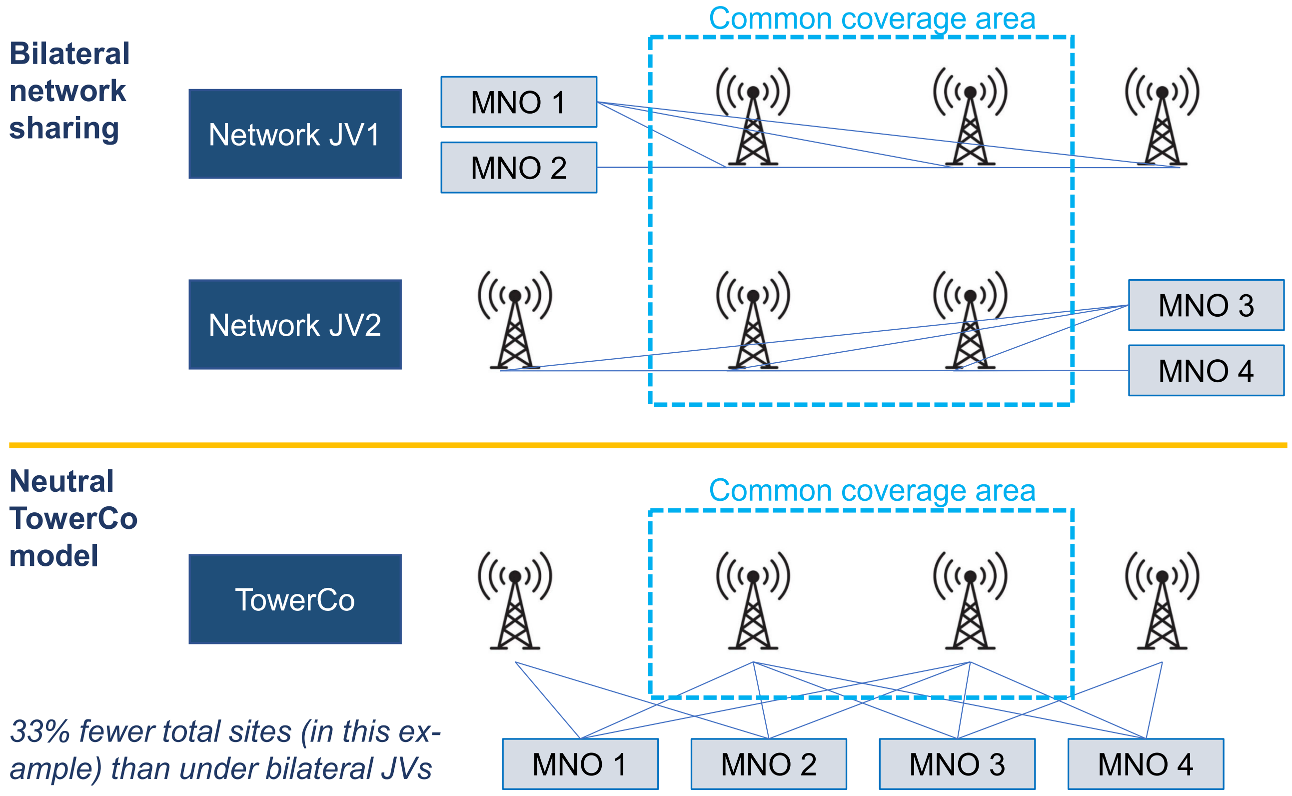
[1] Projections and graphic from 'What is the IoT value chain and why is it important?', Analysis Mason, July 2023
[2] See Verizon corporate announcement, 3 March 2022

Bringing down costs per bit – rationalising passive networks

Rationalising passive network costs is already progressing at pace in many markets with the sale and lease-back of towers.

While open RAN addresses active elements, passive infrastructure remains a drag on returns and should be shared more widely

- Physical towers, power, and backhaul links account for a significant proportion of network costs, and these no longer generate the competitive advantage that existed in the 2G era (when operators differentiated themselves primarily on the basis of network coverage)
- The bilateral network sharing JVs that emerged during the 3G era only allowed two-way sharing, and as well as being a frequent source of friction and dispute between the parties, these severely constrained strategic and operational flexibility
- The sale and leaseback of sites to an independent tower company provides a far more efficient and flexible model



33% fewer total sites (in this example) than under bilateral JVs

Key benefits of tower sales and leaseback:

- Typically generates a gain to the operator on disposal of the asset, with tax benefits often an added bonus
- Allowing the lessor (TowerCo) to monetise additional tenancies improves overall economics
  - Fewer sites are needed in total than under bilateral sharing JVs
- Operators are more likely to deploy on a neutral site than to colocate on one owned and operated by a rival
- Passive infrastructure is used more efficiently, allowing for lease costs below the original opex plus depreciation
- However, operators do need to minimise uncertainties around the terms of future ‘rights of use’ renewals

Bringing down the costs of coverage – LEO D2D communications

Land mass areas with very low demand can be addressed more efficiently with non-terrestrial networks.

Low-Earth orbit satellites will function as ‘base stations in the sky’, effectively wiping out the rural coverage divide

- Remote areas are disproportionately expensive to cover using terrestrial networks: the cost of individual sites are exceptionally high due in particular to challenges relating to power provision, backhaul and site maintenance
- The very high costs are matched against very low traffic and revenues, yielding heavily negative returns and making far-reaching coverage obligations unduly burdensome for commercial operators
- Yet, there is a strong social need for ubiquitous digital access, with pressure on operators from policy makers to constantly expand mobile networks into unprofitable areas
- LEO D2D communications (see Chapter 2) will help address these needs in a far more cost-effective manner, relieving pressure on operators’ capex and opex budgets

Image courtesy of BBC.com

- ➢ Terrestrial mobile networks cover around 90% of the World’s population with 4G (see Chapter 1)
- ➢ This may account for as little as a third of the World’s physical landmass
- ➢ Total landmass accounts for around 30% of the planet’s surface
- ➢ Hence terrestrial mobile networks cover around just a tenth of the planet! LEO’s could cover the remaining 90%

LEO D2D is set to deliver very high social value by bridging the coverage gap – and to provide ubiquitous access to emergency communications from regular smartphones, promoting human safety

Bringing down costs per bit – investing in performance

Per Mbps of capacity, deploying spectrum and efficient technologies are more cost-effective than rolling out new sites.

Total capacity per $ spent needs to increase dramatically

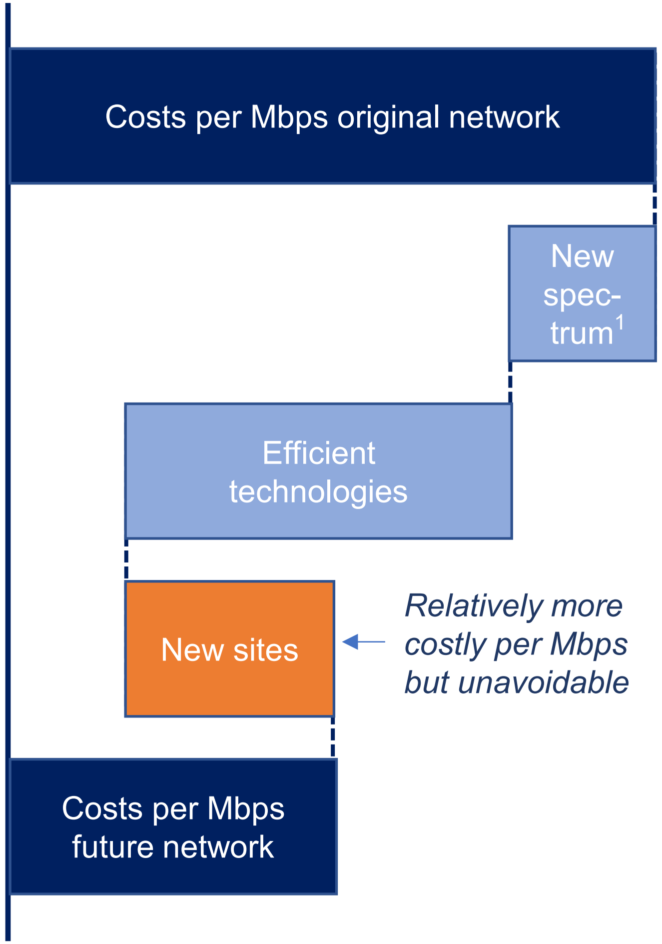
(1) Efficient spectrum deployment

- Operators will need to deploy available spectrum more widely as well as roll out incremental (future) allocations to meet the increased demand for network capacity
- The cost of spectrum is largely driven by public policy (discussed further in Chapter 9), and operators may have limited scope to influence this other than through regulatory advocacy
- However, operators can drive up the capacity per $ spent on existing and new spectrum by investing in technologies that increase spectral efficiency in terms of Mbps per MHz –as discussed in Chapter 2, these include:
  - Upgrading from 4G and 5G NSA to 5G Advanced
  - Deploying higher-order MIMO enhancements (including Massive MIMO where feasible), and/or increasing sectorisation

(2) Efficient network densification

- Even with extra spectrum, significant network densification (additional macro sites and/or small cells) seems inevitable
- Embracing neutral host / TowerCo models is an imperative: as discussed in the previous slide, this helps reduce both passive capex and opex, helping to contain incremental 'total costs of ownership' (TCO)
- Beyond this, operators need to ensure that total capacity delivered per site increases much faster than the extra site TCO – this, again, is achieved by investing in high-performance technologies

Reducing average costs per Mbps
(illustrative – not to scale)



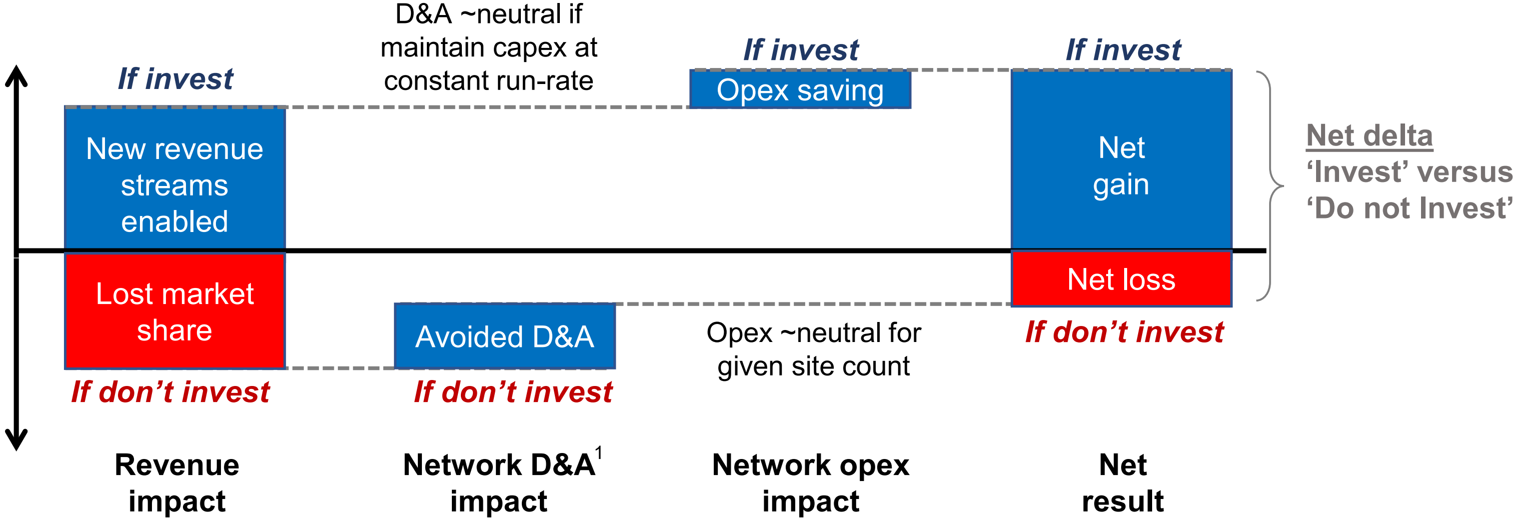
[1] *The scope for reducing costs per Mbps through ne spectrum deployment clearly depends on the total cost of the extra bandwidth.*

The business case for 5G SA and 5G Advanced

Trimming capex is not the answer to financial pressures: the focus should be on service capabilities, and on network efficiency and performance – as well as on reducing opex.

Net impact of investment in mobile technology (illustration):

(not to scale)



Technical obsolescence is never a viable option

In a competitive environment such as mobile, it is essential to keep up with the evolving needs and expectations of key customer groups, as well as to use every opportunity to drive operational efficiencies

The business case for 5G SA (supported by 47 operator-deployments by mid 2023):

- Revenue upside (from Chapter 2): private networks (network slicing), use cases needing low latency and/or high network availability
- market share: 5G SA delivers a more reliable hence consistent service – 5G NSA fails if the 4G signal drops, driving customer churn
- Opex savings: lower energy consumption (no need for 4G resources to support 5G), lower maintenance (fewer radio units needed)
- Asset costs: the transition to 5G SA should be achievable within typical capex/sales ratios, with a broadly neutral impact on D&A[1]

The business case for 5G Advanced:

- Bringing AI into mobile networks to boost capabilities and efficiency is a logical step that mirrors developments in other industries
- Revenue upside: new and improved services, including smart production and productivity
- Opex upside: greater network energy efficiency, streamlined network management

[1] *D&A: asset Depreciation and Amortization – the annualized costs of assets. If one doesn't invest (e.g. in 5G Advanced), one may lose revenues, but avoid the D&A costs associated with the extra investment. The point of the illustration is to highlight the net sources of value from extra investment in technology – we need to take differences in costs into account.*

Key priorities 2023-2030: high-income countries

Overall, capacity expansion is the main priority in high-income countries.

However, 5G coverage gaps also need to be bridged in Europe in particular.

Traffic growth factor in high-income countries is projected to range between 3.4x and 4.4x, with a capacity-growth between 6.8x and 8.8x to consistently meet 100Mbps user experience as per IMT-2020 requirements (see Ch.1)

Key priorities

Additional low band spectrum:

Sub-1 GHz bands remain the most congested and heavily utilised on a per MHz basis (see Chapter 5). Improving indoor as well as wide area network quality will have a disproportionate impact on user experience and competitive advantage

- A renewed focus on freeing up spectrum in the **600 MHz** band for mobile use is called for (see Ch. 4 and 5 for further discussion)
- In some markets, 2x10 MHz at 700 MHz is reserved for PPDR[1], depriving the economy of this valuable resource
  - Using public networks (with prioritised access to bandwidth) for PPDR as is the case in the UK would free up additional 700 MHz spectrum for commercial use

Expanding 5G coverage (especially in Europe):

- With 70% population coverage in 2023, Europe is significantly behind North America and China's 95% (see Chapter 1)

Upgrading to 5G SA and 5G Advanced, increasing MIMO order:

- Operators need to harness the potential of technology, especially **5G Advanced**, to pursue additional revenue streams, strengthen their competitive position, and to drive operational efficiency
- Deploy higher order MIMO across bands to mitigate spectrum insufficiency – drive capacity per MHz and extend cell coverage

Spectrum configurations for 5G advanced

Alternative paths to 5G Advanced:

During our discussions, Huawei' highlighted the following alternative spectrum configurations as providing suitable paths for operators towards 5G Advanced:

(1) Carrier aggregation (CA) across the following 3 TDD bands:

- 3.4-3.6GHz (Band n78)
- Other resources across the wider 3.3-4.2 GHz range (Band n77)
- 2.3 GHz or 2.6 GHz

(2) CA across 2 TDD bands plus mmWave spectrum:

- Band n78 aggregated with 2.3 GHz or 2.6 GHz TDD
- Supplemented with wideband mmWave deployment

(3) CA across TDD plus FDD:

- Band n78 (two carriers) + 2.1 GHz (50 MHz)

(4) TDD plus FDD plus mmWave:

- e.g. 2.6 GHz TDD + 700 MHz + mmWave deployment

Future allocation of U6G (see Chapter 4) could provide further options, with a further 700 MHz of bandwidth to the mobile industry

With the above, 5G Advanced could deliver 5Gbps peak speeds, a cross mobile-generation leap in user experience[2]

[1] PPDR: Public Protection and Disaster Response.
[2] Huawei vision.

Key priorities 2023-2030: emerging markets

Emerging market mobile networks will play a comparatively more important role in broadband delivery due to weaker fixed infrastructures.

Traffic growth factor in emerging markets is projected to range between 3.6x (Southern Asia) and 7.0x (sub-Saharan Africa), with an even higher capacity-growth need to improve customers' mobile data experience (see Ch.1)

- Even if they don't meet the full IMT-2020 requirements, mobile networks in Emerging Markets will need to improve user data-experiences to cater for fixed wireless access (FWA), as well as allowing for mobile short-video resolutions up to 1080p

Operator priorities

Additional low band spectrum:

- To the extent these have not yet been assigned, full **800 MHz** and **700 MHz** allocation and deployment should be the highest priority to improve indoor and wide area cell edge performance[1]

Additional mid band spectrum:

- Allocating and deploying **2.3GHz**, **2.6GHz** and full **3.4-3.8GHz** is essential to meet the higher % growth in mobile data demand in emerging markets (see Chapters 1 and 5)
- Additional capacity will also allow operators to offer better and more cost-effective FWA services

Expand MBB coverage[2]:

- The population coverage gap for MBB is generally far wider in emerging markets
- In addition to the social cost of the coverage divide, reducing it will allow operators to address latent demand for mobile services
  - Especially given a lack of rural fixed broadband substitutes
- Additional low band spectrum would enable operators to address these needs more cost-effectively

Policy priorities

Additional spectrum awards:

- To allow the industry the address the growing broadband needs of consumers and businesses, emerging market regulators need to accelerate the allocation of both low and mod-band spectrum

Technology neutrality:

- Where not already implemented, spectrum usage-rights should be awarded on a technology neutral basis
  - Operators are invariably better placed to decide on the optimal mix of technologies to deploy across bands
  - The absence of technology neutrality forms a barrier to optimal deployment and is liable to reduce the efficiency with which spectrum is utilised

Spectrum pricing reforms:

- High spectrum costs drain operator capital, impeding investment
- In particular, these are excessive and need to be significantly reduced in Pakistan, Bangladesh and Indonesia (see Chapter 9)
- Payment methods should also be reformed, to allow licence fees to be spread more evenly during the licence term (thus avoiding large, sudden and potentially disruptive funding calls)

[1] In some emerging markets, up to 2x20 MHz at 700 MHz is occupied by the state security services – depriving the economy of an essential input. Allocating at least 2x10 MHz of this for public mobile use should be a key priority, given the high value of the band.
[2] While LEO D2D will likely play a role, terrestrial coverage makes sense where demand exceeds future LEO capacity per square Km.

Part II – Mobile Spectrum Evolution

Quantifying spectrum need 2024-2030

Chapter 4 Global spectrum allocations and roadmap

Chapter 5 IMT spectrum need across regions

Chapter 6 Managing the transition to 5G advanced, readying for 6G

Chapter 7 Operator business case for additional spectrum

Part II

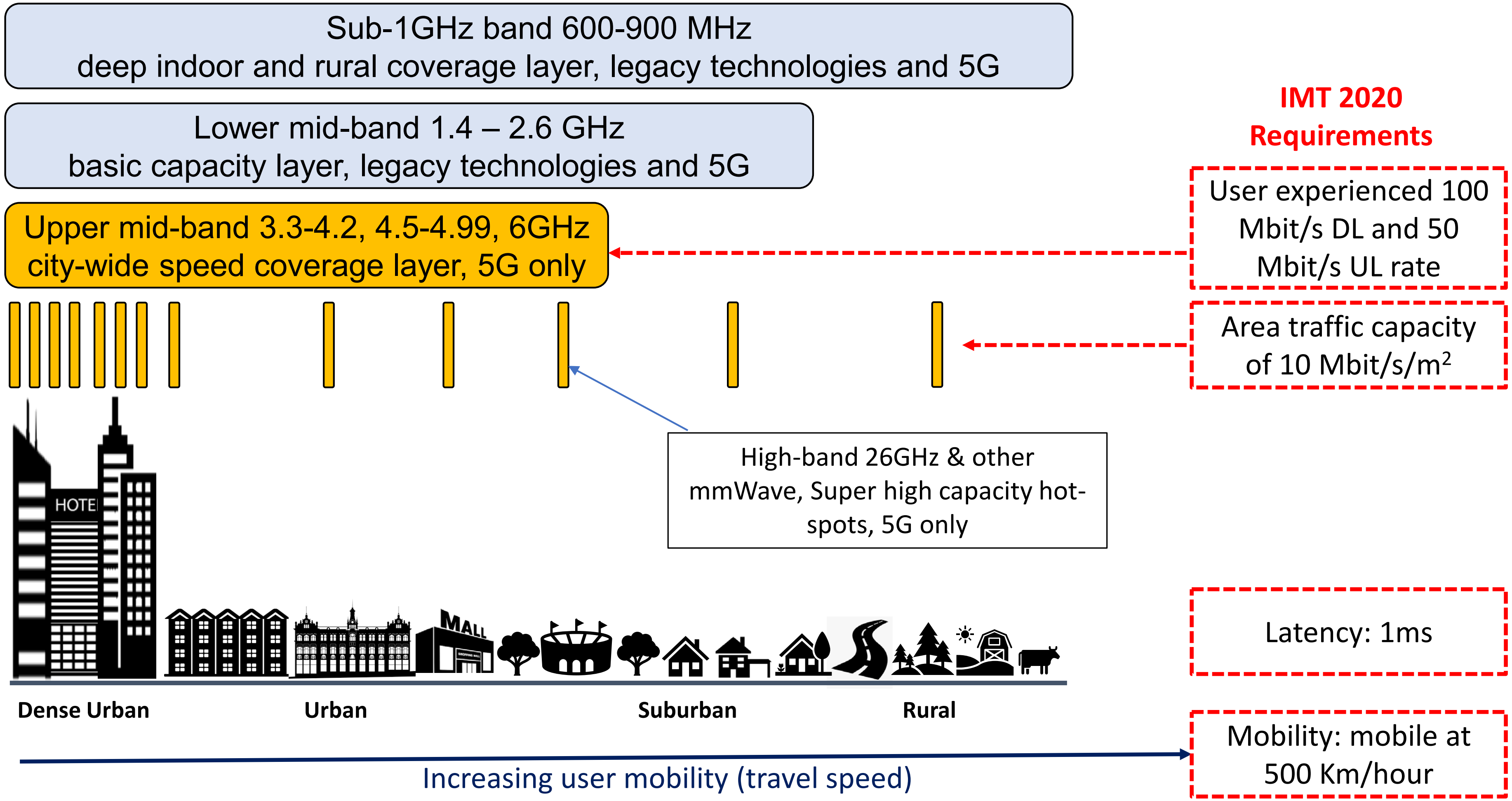
4

Global spectrum allocations and roadmap

Band priorities and state of play across ITU Regions 1, 2 and 3

Primer: mix of spectrum to meet the IMT 2020 requirements

A mix of spectrum spanning low to high bands is needed to meet the IMT 2020 requirements specified by the ITU.



- Low frequency bands generally provide both wide area and deep indoor coverage, and support mobility when users travel at higher speeds
- Higher bands provide extra capacity where demand is more densely concentrated

Primer: key band categories

With the exception of the C-band and mmWave, one cannot really speak of 5G versus 4G spectrum: over time, all bands will migrate to 5G.

Decreasing propagation (range) – so less good for coverage →

Increasing amounts of available bandwidth – good for capacity →

Greater scope for massive MIMO – good for capacity and cost per bit →

More scope for wide band deployment – good for speed performance and lower cost per MHz deployed →

Low band
600-900 MHz

e.g. 600, 700, 800, 900 MHz

Superior propagation make these best for wide area and deep indoor coverage

- But most scarce spectrum
- More limited scope to extend capacity per MHz through higher order MIMO deployment
- 700 MHz: 5G coverage layer in ITU Region1; used for 4G elsewhere, but will be refarmed to 5G over time
- 600 MHz: 700 MHz-equivalent in US/Canada, possible future allocation in other markets

Lower mid band
1400-2600 MHz

e.g. 1800, 2100, 2300, 2600 MHz

Good compromise between propagation characteristics and capacity potential

- Historically, 1800 MHz used for 2G, AWS and 2100 MHz for 3G
- 2300 MHz and 2600 MHz were early 4G bands where available, adding to 1800 MHz spectrum re-farmed from 2G to 4G
- 2600 MHz and 2300 MHz: 5G candidate bands in some countries

Upper mid band
3.3GHz-7GHz

e.g. 3.3-4.2, 4.5-4.99, 6 GHz

Newer to IMT and much more plentiful – key 5G capacity resources, allowing highly efficient, wide band deployment

- 3GPP standardised radios and terminals available for the C-Band (band n77, 3.3-4.2GHz)
- C-band (400 MHz in Europe) is the first mid band in which a channel width of 100 MHz can be used – a 5G innovation
- Rolling out 5G in the C-Band is an overriding policy objective; 3.4-3.8GHz used in most countries
- Good combination of propagation and capacity for cities

High band (mmWaves)
> 10GHz

e.g. 26, 28, 39 GHz

Effective at addressing areas with very high traffic density with extreme peak data rates – FWA[1] is a prime use case

- Not suitable for contiguous wide area coverage given the large number of sites this would require
- Adding mm wave spectrum will increase the spectrum used by mobile operators by up to 6000 MHz (dwarfing the amount of spectrum deployed by mobile operators as of 2020)
- 66 GHz is not as yet harmonised as an international IMT band, but is being discussed as a potential further 5G candidate band

[1] FWA: Fixed Wireless Access

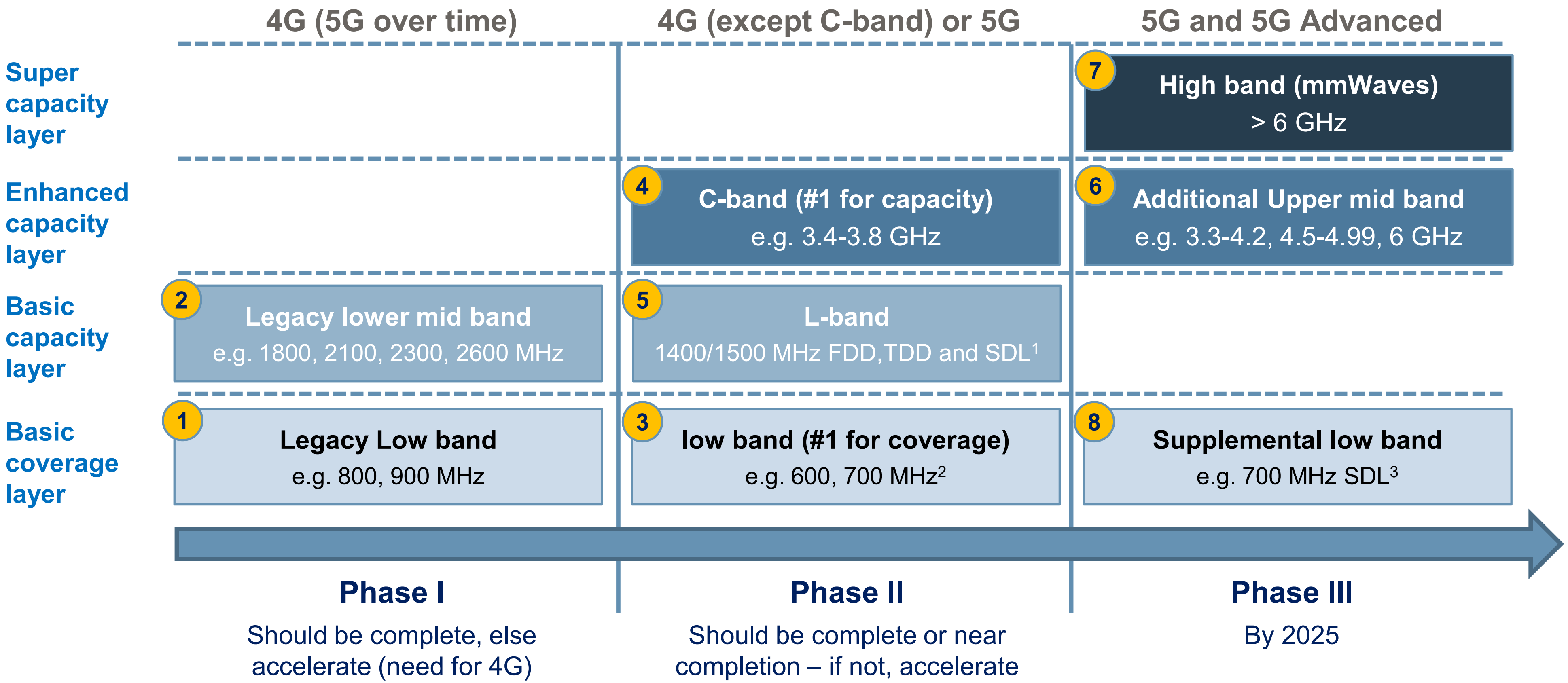
Spectrum award and deployment priorities

Deployment priority needs to take account of the need to address 4G demand while driving migration to 5G.

The strength of the device and equipment ecosystem for given bands also influences timing.

Providing a good coverage layer is essential both for the 4G and 5G experience.

700 MHz can be used for either or both in the near term[2].



- In 'Phase II', the C-band and 5G candidate low bands should ideally be awarded at the same time; the urgency is generally slightly greater for 700 MHz, because this can immediately be used to expand 4G capacity and improves indoor coverage and cell edge performance
- In 'Phase III', additional Upper mind band and High band will be important to serve very high traffic density areas and FWA
- 700 MHz SDL could be a useful additional resource to deploy over time, helping relieve low band congestion – however, 700 SDL deployment is arguably the lowest priority because its ecosystem is weak and the potential to establish significant international scale seems limited

Bands n77 (3.3-4.2GHz), n96 (6GHz) and mmWave bands are deemed highly important to deliver the full benefits of 5G Advanced[4]

[1] SDL: Supplementary downlink. [2] 700 MHz can be used for extra 4G capacity but this would weaken 5G coverage making it (relatively) less attractive. [3] 700 MHz SDL: 20 MHz in FDD centre gap awarded in some European markets – low band capacity and cheap to deploy for existing 700 MHz users.
[4] Source: discussions with Huawei

Summary of WRC-23 outcome

Wide international harmonisation of frequencies for mobile use is key to driving benefits of scale and to support the device and equipment eco-systems.

Significant traction in key bands including 600 MHz, 3.3-3.8 GHz and the Upper 6 GHz band[1]

Band	WRC-23 Outcome
470-694 MHz	• 11 Middle East countries: allocated 614-694 MHz to mobile (except aeronautical mobile) service (primary) with IMT identification • 43 European countries and Uzbekistan: allocated 470-694 MHz to mobile (except aeronautical mobile) service (secondary) • 8 African countries: allocated 614-694 MHz to mobile service (secondary) • **El Salvador and Jamaica** joined FN 5.308A of 614-698 MHz for IMT • WRC-31 will consider again the identification of this band for IMT in Europe
3.3-3.4 GHz	• **Region 2** (Americas): allocated to mobile service (primary) with IMT identification • 22 African, Middle East and APAC countries: allocated to mobile service (primary); 17 countries: identified for IMT; Total number of countries with primary mobile allocation: 50 countries in Africa, 19 APAC, and 16 Arab countries (including 5 African countries)
3.6-3.8 GHz	• Region 1 (Europe, Africa, Arab and CIS regions): allocated 3.6-3.8 GHz to mobile service (primary); identified for IMT in Africa and Arab regions, except for six African countries that identified 3.6-3.7 GHz for IMT • **Region 2** (Americas): identified 3.6-3.7 GHz for IMT; 15 American countries / territories identified 3.7-3.8 GHz for IMT
4.8-4.99 GHz	• AI1.1 outcome: NOC. Regions / countries that supported 4800-4990 MHz IMT at WRC-23: ATU, RCC, China, Vietnam, Indonesia, Cambodia, Laos, **Argentina, Brazil, Chile, Colombia** • Nigeria, Kenya, Mozambique, Sudan, Tanzania decided to opt out of FN. 5.441B; Some of these countries made statements to the Plenary, to reserve their sovereign right to implement IMT systems in the 4800-4990 MHz band
6425-7125 MHz	• Region 1 (Europe, Africa, Arab and CIS regions): identified 6425-7125 MHz for IMT • Region 3 (APAC): identified 7025-7125 MHz for IMT; 3 countries identified 6425-7025 MHz for IMT • **Brazil and Mexico**: identified 6425-7125 MHz for IMT • Harmonized technical conditions for protection of FSS would not overly restrict the deployment of macro-cellular IMT base stations in the 6425-7125 MHz band
10-10.5 GHz	• **12 Latin American countries** identified 10-10.5 GHz for IMT; Use of this band for IMT is only intended for microcell base stations

Note: 'allocation to mobile' here does not necessarily mean actual award of spectrum to operators – but it is a first step towards assignment

[1] *Source: GSA presentation at Latam Spectrum Management Conference, February 2024.*

State of play: band b71 and n105 – 600 MHz

600 MHz represents a valuable additional low band resource. H

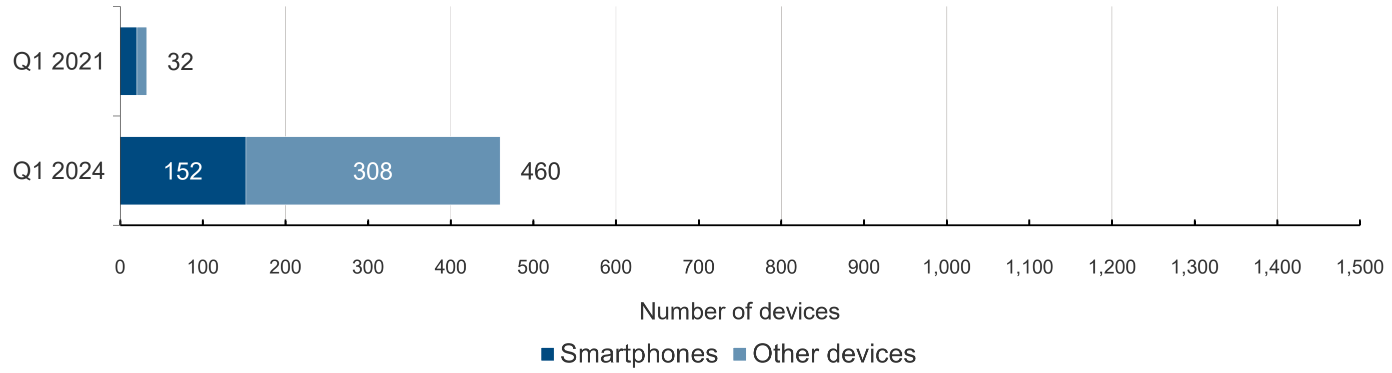
However, it is yet to become available in many regions.

2x35MHz (b71) or 2x40 MHz (n105) of prime spectrum, with rapidly evolving ecosystem

- 600 MHz is still occupied by digital terrestrial television (DTT) in many markets, limiting the current international scale of its mobile ecosystem – nevertheless, the number of mobile devices supporting the band grow by over 14x between Q1 2021 and Q1 2024
- With the declining global importance of linear broadcasting, additional reallocations of DTT spectrum to mobile seems likely over time

ITU Region 1	ITU Region 2	ITU Region 3
2x35MHz (617-652MHz with 663-698MHz)	2x35MHz (617-652MHz with 663-698MHz)	APT: 2x40 MHz (612-652 with 663-703MHz)
▪ Nor available in Europe until at least 2030 (CEPT[1] decision), but possible future reassignment from DTT to mobile as part of '3rd Digital Dividend' ▪ Saudi Arabia and other GCC states considering 600 MHz awards	2x35MHz allocated in some markets ▪ USA: b71 auctioned in 2017 ▪ Canada: auctioned in 2022 ▪ LATAM markets considering 600 MHz auctions, including Mexico and Brazil	▪ India: plans to auction band n105 (TRAI adopted APT band-plan in 2022)

Band support (based on GSA data)



[1] *CEPT: coordinating body of European postal and telecoms administrations.*

State of play: band n77 – 3.3 GHz to 4.2 GHz

Band n77 is especially important to deliver the full benefits of 5G Advanced.

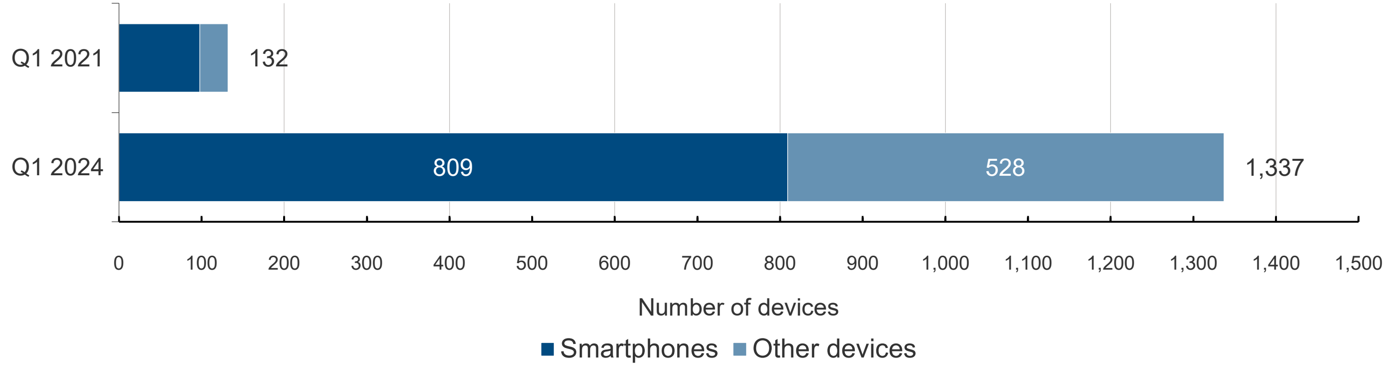
Band n77 is one of the most mature 5G bands, with 200-400 MHz available in many markets

- Globally, 3.4-3.6 GHz (200 MHz in sub-band n78) is most widely allocated to mobile, followed by the wider 3.4-3.8 GHz range (400 MHz)
- 3.6-3.8 GHz is occupied by alternative users in some markets – e.g. Satellite or alternative (non-MNO) FWA networks

Around **150 operators** have or are deploying n77/n78 globally, with a total of around 270 operators licenced in these bands[1]

ITU Region 1	ITU Region 2	ITU Region 3
Allocation examples: ▪ UK: 400 MHz in 3.4-3.8 GHz awarded to mobile, Ofcom considering shared (mobile/non-mobile) across 3.8-4.2 GHz ▪ France: 3.6-3.8 GHz to be awarded to operators in 2026 ▪ Kenya: 3.4-3.6 GHz allocated to IM 3.6-3.8 GHz previously licenced for satellite	Examples: ▪ North America: 3.55-3.7 GHz for unlicenced 'CBRS' use[2] ▪ Brazil: Released 400 MHz of spectrum to operators in 2021 ▪ Argentina: Awarded 250 MHz within 3.3-3.6 GHz to operators in 2023 ▪ However, Mexico continues to delay its 5G auction (as of April 2024)	Examples: ▪ Australia: Spectrum across 3.4-3.6 GHz was awarded in 2023 ▪ Malaysia: 200 MHz of spectrum was awarded to the single national wholesale operator, DNB, in 2022 ▪ Indonesia: Spectrum release for 5G in this band is expected in 2025 ▪ Philippines: 200 MHz awarded in 2020

Band support (based on GSA data)



[1] *Source: GSA 5G Market Snapshot, February 2023*
[2] *CBRS: Community Broadband Radio Spectrum*

State of play: band n96 ('U6G') – 6 GHz

Allocation of the U6G band for licenced mobile use would be of high socio-economic value: it would allow further wideband deployment in FR1[1], enabling the full benefits of 5G Advanced.

Introduction of the U6G band would yield up to 700 MHz of bandwidth, between 6.425-7.125 GHz

- WRC-23 identified the band for IMT use across ITU-R Region 1 (Europe, Africa, Middle East, CIS states)
- It also identified the top portion of the U6GHz band (7025-7125MHz) for IMT across Region 3 (Asia and Oceania), whilst Brazil and Mexico (in Region 2) identified the full band
- Use of the band will likely be subject to certain limitations to protect existing satellite services
- Due to the recent identification of this band, no mobile devices support it as yet, however vendors have already demonstrated test calls using the band
  - It is therefore expected that supporting equipment and devices will be available in a timely manner, as more countries announce plans to award the band – especially given the strong international interest on this band
- In early 2024, Hong Kong was the first administration to move forward with plans for spectrum release to mobile operators in the band – announcing its intention to assign 400 MHz of the band before the end of Q1 2025

[1] *FR1: Frequency Range 1, representing all low, mid and upper-mid bands up to and including 6GHz.*

State of play: mmWave bands

Despite their more limited propagation, mmWaves will play a role in high-traffic density areas, supporting 5G advanced and 6G in the future.

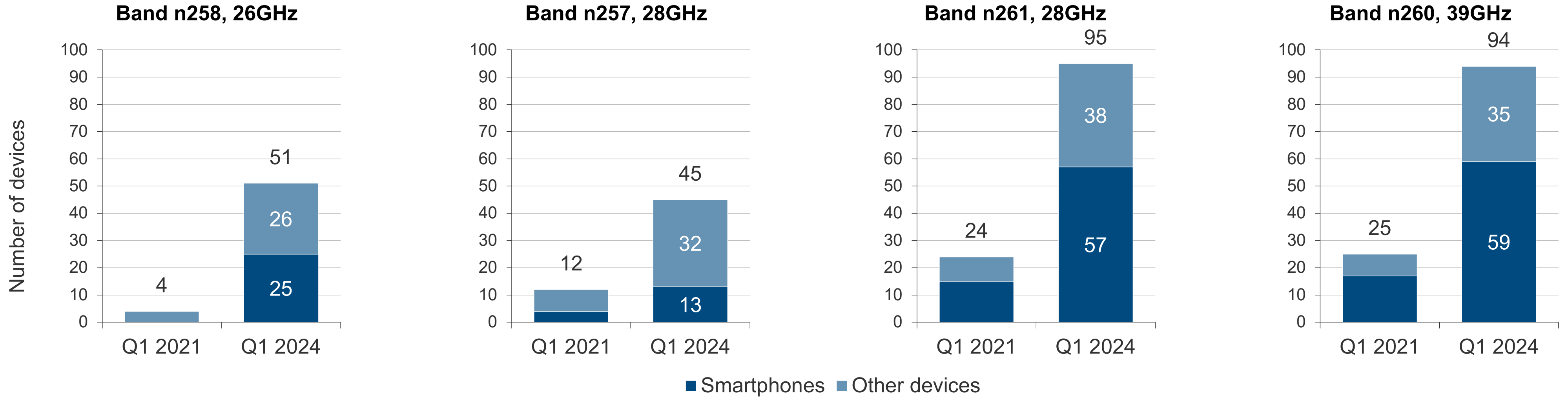
Huge bandwidth available in mmWaves, but poor propagation limit these shorter range and line-of-sight transmission

- 3.25 GHz available in band n258 (24.25-27.5GHz) in Europe and China[1]
- 3 GHz available in band n257 (26.5-29.5GHz) in North America, Japan, South Korea[1]
- 850 MHz available in band n261 (27.5-28.25GHz), for operation alongside band b260 in the US, in which 3GHz is available (37-40GHz)[1]

Over **25 operators** have or are deploying bands n258, n257 or n261 globally, with a total of around 170 operators licenced in these bands, while over 25 licences have been issued to operators in the n260 band[2]

ITU Region 1 – Awards/deployments[3]	ITU Region 2 – Awards/deployments[3]	ITU Region 3 – Awards/deployments[3]
▪ Denmark: both n258 and n257 ▪ n258 a.o. in Austria, Croatia, Estonia, Finland, Italy, Norway, Slovenia, Spain ▪ n257 in Czech Republic, South Africa	▪ US: n258, n261 as well as n260 ▪ n258 in Brazil, Chile	▪ Singapore: both n258 and n257 ▪ n258 in India, Thailand ▪ n257 in a.o. Hong Kong, Indonesia, Japan, Malaysia, Taiwan, Vietnam

Fast growing global mmWave band support (based on GSA data):



[1] Source: Mi-Wave (miwv.com)
[2] Source: GSA 5G Market Snapshot, February 2023
[3] Source: Wikipedia list of 5G NR networks, accessed March 2024

Potential further bands[1]

A further 1,780 MHz may become available for IMT between 7 and 15 GHz.

Further bands may potentially be allocated to IMT between 7 and 15 GHz

7.125 to 8.4GHz:

- New band to be studied for 6G (agenda item for WRC-27)
- Up to 1,275MHz potentially available, except 500 MHz between 7.25 and 7.75MHz in Europe, currently used by NATO

14.8 to 15.35GHz:

- New band to be studied for 6G (agenda item for WRC-27)
- Up to ~500 MHz potentially available

12.7 to 13.25GHz (US only):

- Within US spectrum pipeline, outside WRC process
- Up to ~500 MHz for exclusive mobile broadband licensed use

Nokia assessment:

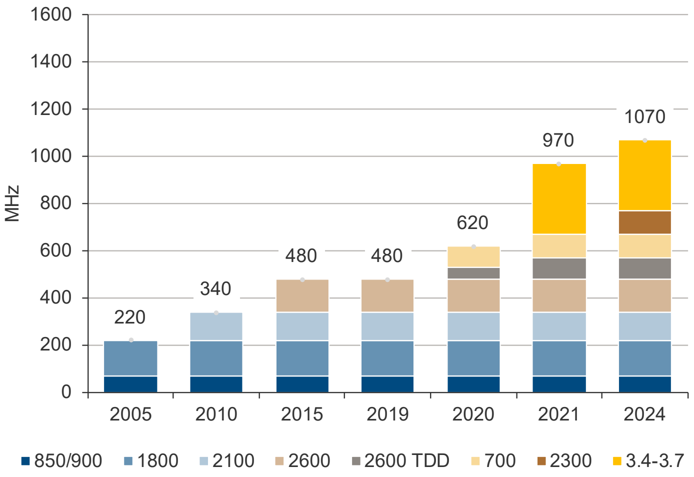
- Spectrum within the upper-mid range from 7 to 15 GHz is regarded as the ‘golden bands’ for 6G due to the potential availability of wider spectrum than that in FR1 for high throughput, as well as the more favourable propagation characteristics of the frequencies as compared to millimeter waves in FR2 (24-51.2 GHz)
- Critical to the attractiveness of [this potential new] spectrum for mobile broadband is the ability to re-use the existing site grid on which the current network is deployed
- Spectrum around 7 GHz shares many similarities with the 3.5 GHz spectrum band: using the same maximum transmit power but two times the bandwidth and four times the number of antenna elements and transceivers chains, future 6G extreme MIMO can provide comparable (indoor) cell edge throughput as 5G deployed in the 3.5 GHz

[1] *Source: Nokia white paper ‘Coverage evaluation of 7–15 GHz bands from existing sites’, April 2024.*

Typical allocations and spectrum roadmap in different regions

With new spectrum for 5G, the amount of spectrum used by mobile operators to satisfy the growth in mobile data will double between 2020 and 2025.

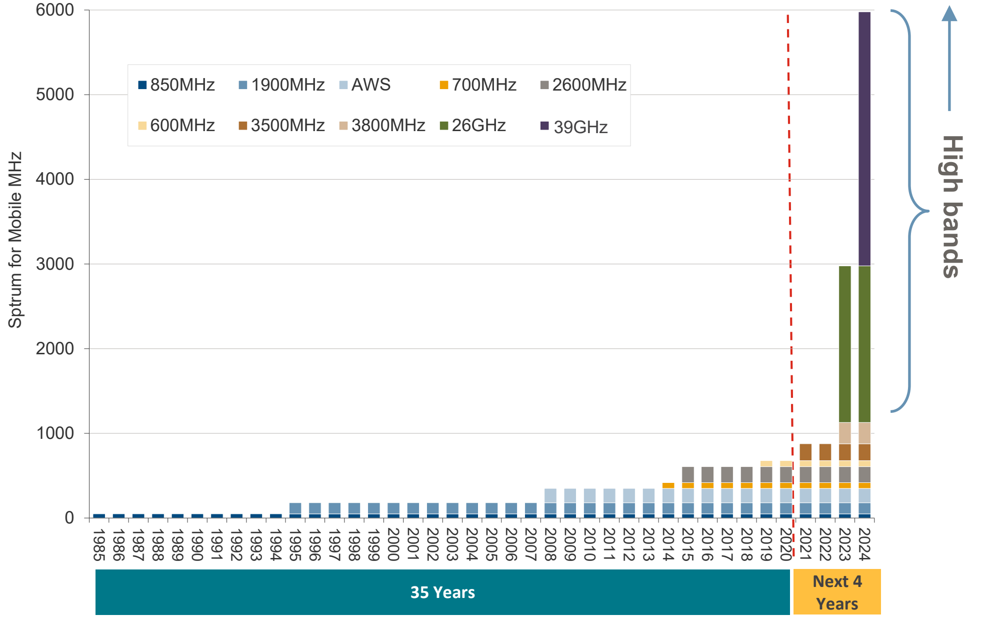
Typical low and mid band spectrum allocated to mobile in Asia



Indicative 'averages' of current and future allocations in low to upper-mid bands in ITU Region 3 (Asia Pacific).

Spectrum roadmap in Canada

Almost 5x more MHz than low-to-mid bands



Typical spectrum used by mobile in Europe by 2023

Legacy bands	New "5G" bands
Low bands 700MHz 2x30 MHz 800MHz 2x30 MHz 900MHz 2x35 MHz Total 190 MHz FDD	**Upper mid-bands** 3.5GHz 400 MHz
Lower mid-bands 1800MHz 2x75 MHz 2100MHz 2x60 MHz 2600MHz 2x70 MHz 2600MHz 50MHz Total 410 MHz FDD, 50 MHz TDD	**High bands** 26GHz 1000 to 3000 MHz TDD

User experienced data rate 100 Mbit/s

Area traffic capacity of 10 Mbit/s/m²

Based on typical situation in Europe in 2021

- Up to 525 MHz of spectrum has already been released to operators in some markets
- By 2021, once spectrum in the C-band, in 2300 MHz and 2600 MHz is assigned, the spectrum used by mobile operators in those markets will have increased to 1,155 MHz
  - i.e. more than double the amount used in 2019
- In the EU, on aggregate, mobile operators will typically hold 190 MHz of low bands spectrum, 460 MHz in lower mid bands plus 400 MHz in upper mid bands by the end of 2023, with some variation between countries

[1] *Taking account of the fact that certain identified IMT bands have yet to be allocated in some markets.*

5

IMT spectrum need across regions

Assessing low, mid band and high band spectrum demand from a societal perspective, for capacity and coverage quality

Assessing total spectrum need: key considerations

While the drivers are similar, spectrum need from a societal versus an operator perspective reflects distinct considerations.

The drivers for spectrum demand (for capacity) include total data consumption, as well as the concentration of traffic in conjunction with speed experience targets – albeit the interests of society and of operators may differ

- The growth in data consumption, with a 4x projected factor increase globally between 2023 and 2030 (see Chapter 1), drives demand for an average 4x global increase in capacity across whole networks
- User-speed experience targets, such as the 100Mbps per user specified in the ITU 2020 Requirements for 5G (see Chapters 1 and 2), drive significant further increases in capacity – circa 2x extra, by our estimates, to meet this objective, implying **8x** extra capacity need
- To deliver these network-wide increases in capacity, operators will need to: (1) secure and deploy **additional spectrum**, as well as (2) densify their networks and (3) deploy higher-order MIMO antenna systems to boost capacity per MHz per site (see Chapters 2 and 3)

However, *total* spectrum need is driven by the demand for capacity in the busiest parts of the network – typically accounting for a small proportion of the total network footprint (in square Km) and of deployed sites

- These include dense urban areas in which people tend to be highly concentrated during busy periods, as well as sports stadiums, both of which require exceptionally high levels of capacity (in Mbps) per square Km
- Spectrum-bandwidth needs in these areas tend to significantly exceed the national average across urban categories

Key societal considerations

- Meeting the communications needs of consumers and businesses (at accessible prices) in all circumstances, including the most concentrated areas
- Unmet demand has an impact on welfare, and economic productivity and growth
- Avoiding this drives the total societal need for mobile spectrum

Key operator considerations

- Meeting the bulk of demand is essential to operators, to defend or extend their competitive positions
  - Unmet demand (e.g. due to spectrum insufficiency) is less of a concern to operators if rivals are equally constrained
- 'Spectrum need' for operators is related to 'spectrum value', which reflects network cost-avoidance potential from extra spectrum and/or market share trade-offs[1]

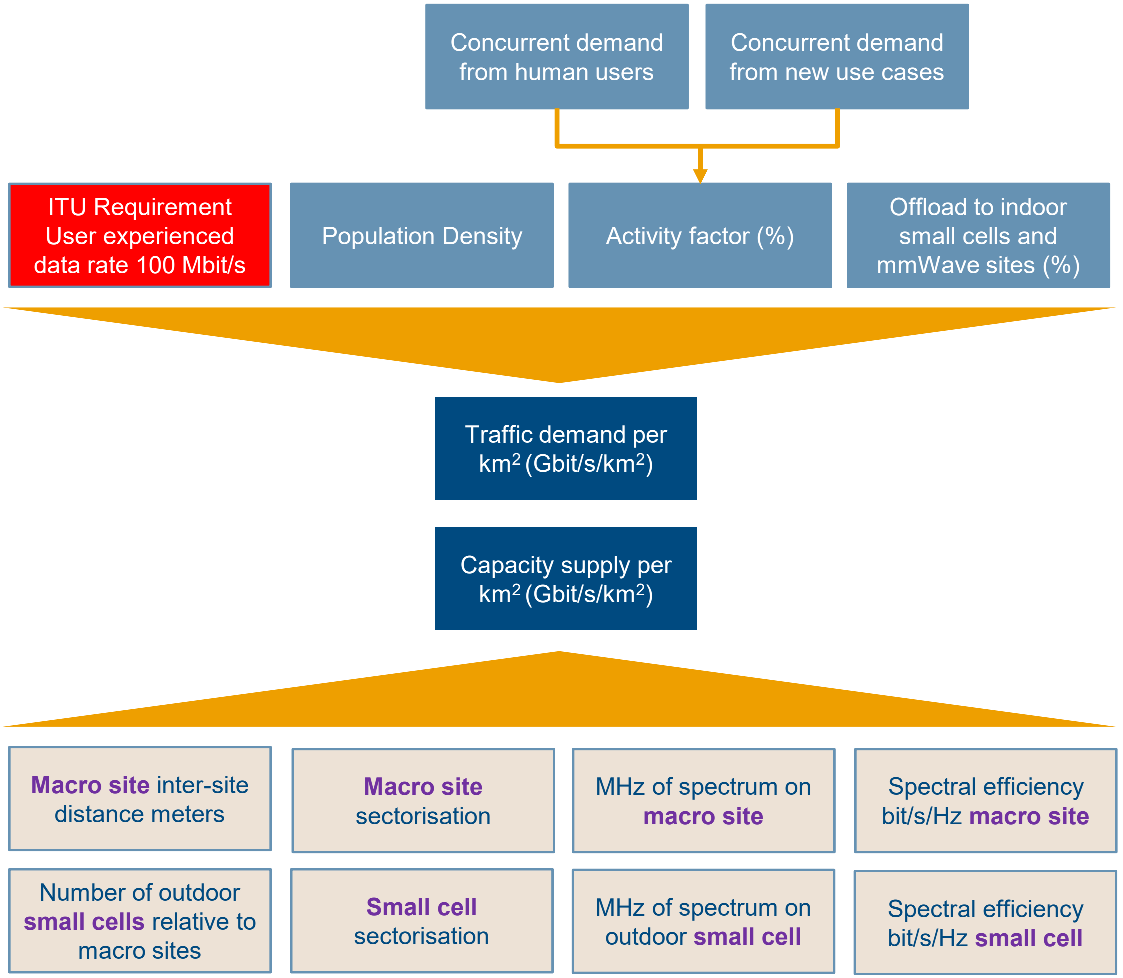
In this chapter, we focus on spectrum 'need' from a societal perspective, as opposed to spectrum 'value' for operators (addressed in Chapter 7) – we start with spectrum need for capacity, followed by analysis of low band need for coverage quality

[1] Operators express spectrum demand in terms of what they are willing to pay for it. This will depend largely on the potential for network cost avoidance (e.g. potential costs per Mbps with versus without additional spectrum), as well as the value of market share gains or losses that may be associated with different shares of mobile spectrum.

Quantifying total spectrum bandwidth need: methodology

Spectrum 'need' (as opposed to 'value') can best be assessed by focusing on the busiest parts of the network, at the point where alternatives to spectrum deployment become impractical (or prohibitively expensive).

Traffic demand and capacity supply model



Increased network-wide demand for capacity entails higher demand for spectrum, but the relationship between the two is not necessarily linear

- The need for spectrum is driven by traffic density so we need to analyse traffic demand in areas with high population densities, i.e. cities
- There is a high degree of uncertainty over how much simultaneous capacity will be required by different users within any given area
  - We use population density in cities as a proxy for traffic density, to estimate the minimum or floor capacity requirement
  - While traffic generated by connected vehicles, 5G video cameras and video-based sensors could potentially exceed traffic generated by human users in certain areas[1], total traffic intensity is likely to remain highest where people are most concentrated

Demand-side assumptions

- The IMT-2020 requirement: DL user experienced data rate of 100 Mbit/s and 50 Mbit/s uplink
- The population density (proxy for traffic density)
- An assumption of concurrent demand from human users and new use cases (the 'activity factor')
- An assumption of how much of the traffic demand would be satisfied offloading to high bands (24 GHz and above) and to indoor small cells

[1] *Our earlier-quoted global projections of IoT traffic (based o external forecasts) may be severely understated, as outlined in Ch.1 (with tethered wearable IoT traffic likely reflected under MBB). Moreover, IoT traffic from the use of body cams, LIDAR cameras and CCTV (increasingly connected via cellular), in particular, are likely to be concentrated in densely populated areas.*

Quantifying total spectrum bandwidth need: key assumptions[1]

Spectrum need projections shown in this report span a sample of 4 developed and 6 emerging-market cities with densities above 8000 inhabitants per square km (out of an original sample of 35).

Key modelling assumptions for dense urban environments

Band	Category	Average inter-site distance (m)	Number of sectors	Average DL/UL spectral efficiency (bit/s/Hz)
700, 800, 900 MHz	Macro site; Low bands	400	3	1.8 / 1.8
1800, 2100, 2600 MHz	Macro site; Lower mid-bands	400	3	2.2 / 2.5
3.5 GHz	Macro site; Upper mid-bands	400	3	6.0 / 4.1
Additional mid-bands	Macro site; Mid-bands	400	3	6.0 / 4.1

Density of macro sites

- In a typical city, macro sites use low and mid bands, while small cells only use upper mid bands; the typical inter-site distance for macro sites is ca. 400m

Spectral efficiency factors and design margins

- We model on the basis of 5G in all bands, and assume that 600 MHz in low and mid bands will be FDD, with the remainder TDD using a 3:1 downlink (DL) to uplink (UL) ratio
- The ITU-R target for dense urban eMBB is 7.8bit/s/Hz and could be achieved by using 64-element MIMO; we apply a blended average, reflecting a mix of MIMO configurations[2]
- To manage interference, a design margin of at least 15% is required; i.e. 15% of the nominal capacity cannot be used

Activity Factors

- We model scenarios with Activity Factors ranging from 5% to 25% – reflecting peak concurrent data sessions per square Km as % of the recorded population-density in a given city
  - This would include connections from people that are within a given area at that time, whether they live there or not
  - It also includes concurrent non-human (IoT) data sessions
- Moreover, we should consider the busiest parts of a city rather than an average across a city
  - The fact that average (rather than maximum) density is taken as a reference metric points towards higher Activity Factors

Role of small cells and mmWaves

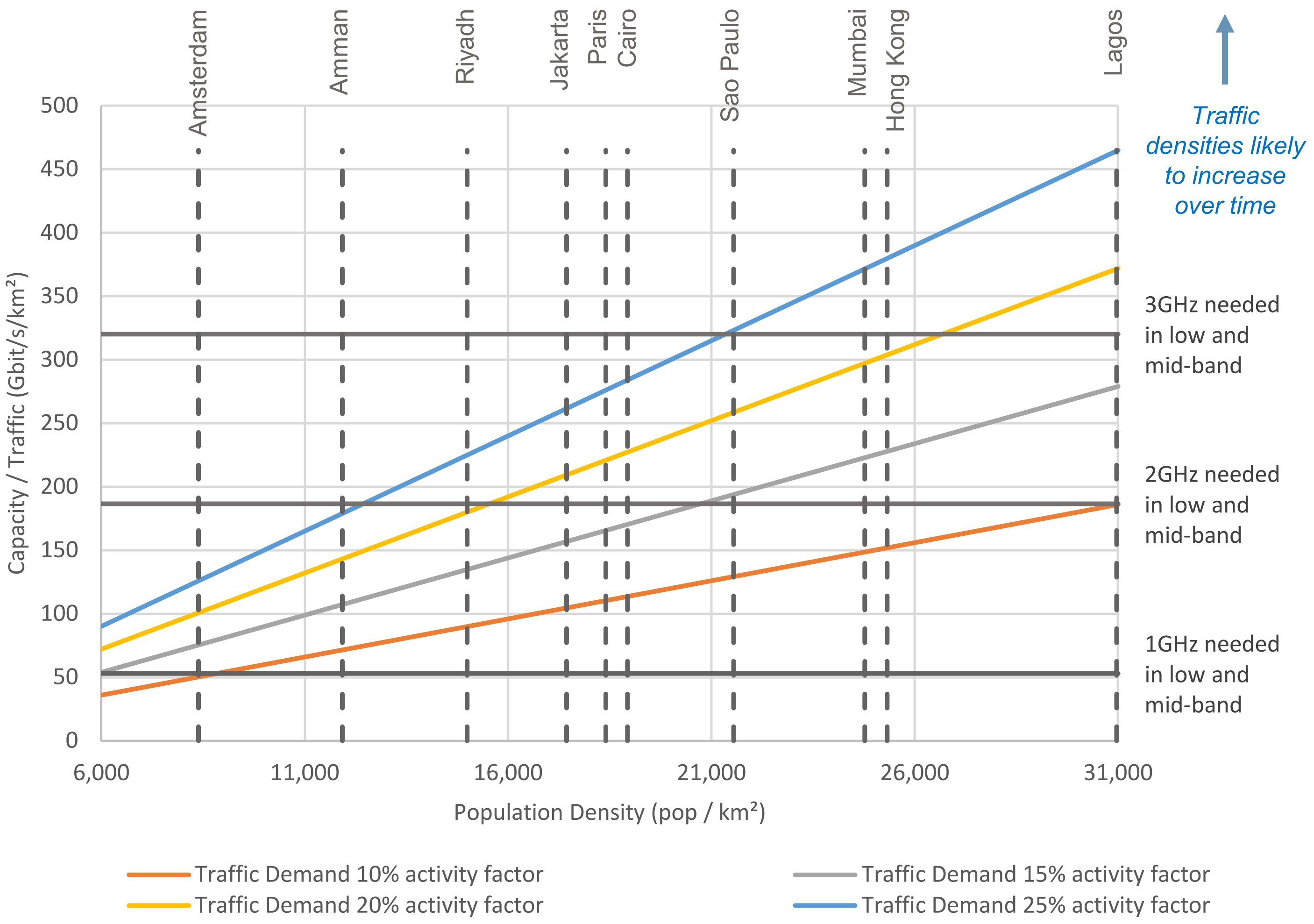
- Small cells and mmWave deployments would not provide contiguous coverage but would be used to fill in ‘speed coverage holes’
- Capacity from small cells and mmWaves is not modelled directly: our results reflect different scenarios on the % of traffic offloaded onto small cells and/or mmWaves
- However, to calculate total area capacity (in Gbps per square Km) in the next slide, we do assume:
  - 3 (single-sector) small cells per macro site
  - Deployment of all upper-mid band spectrum on small cells, with an efficiency factor of 3.7 bits/s per DL MHz
- Levels of offload to small cells and mmWaves are generally likely to increase with higher activity factors

[1] From ‘IMT spectrum demand – Estimating the mid band spectrum needs in the 2025-2030 time frame’, a Coleago report for the GSMA (June 2021). The quoted spectral efficiency factors are per sector. [2] 128T MIMO is also becoming available (see Ch.2) – however, massive MIMO deployment is unlikely feasible in all bands concurrently, due to size and weight limitations on typical sites, which is why a blended factor is used.

Scenario outcomes: MHz needed for the 100Mbps downlink speed requirement[1]

The higher the population density and the higher the levels of concurrent usage ('activity factor'), the higher the spectrum need.

DL area traffic demand and low to mid band spectrum need (assuming 35% traffic offloaded to high bands and indoor small cells)



Activity factors may be expected to increase over time in all markets

- A 15% activity factor may be a realistic assumption for 2025[2] in a high-income country and will likely grow by 2030
- 15% might not be immediately applicable for low-income markets
  - Albeit mobile broadband use (including FWA) is likely to expand substantially in EMs where fixed broadband infrastructure is weaker
  - By 2030, Activity factors in emerging markets could match those in DMs in 2025
- In areas with a population density greater than 6,000 per sq.km, more than 1GHz of low and mid band spectrum is likely needed to deliver the IMT 2020 requirement for 100Mbps DL
- Given typical current holdings below 1,200 MHz in low and mid band, additional mid band is likely needed in areas with >8000 capita per sq.km
  - In less dense areas, additional mid bands would help reduce overall site-density (environmental benefit)

[1] Based on our 'IMT spectrum demand' report (ibid) and the underlying model, with selected sample city data-points added.
[2] Note that the Activity Factor is not related to the data speeds of individual connections – these may not all be delivered at 100Mbps (in 2025) – the point of the analysis is to estimate spectrum need to provide these with the 100Mbps DL experience specified by the ITU IMT 2020 Requirements.

Scenario outcomes: MHz needed for the 100Mbps DL plus 50Mbps UL requirements

The uplink speed requirement could add between 0 and 30% to total spectrum need.

The IMT 2020 requirements also specify a 50Mbps UL speed requirement, which in some instances adds to total spectrum need

- In areas with lower traffic densities, the uplink portion of the spectrum is sufficient to cover the UL requirement
- In areas of very high traffic density, the average uplink portion of spectrum is insufficient to meet the UL requirement, because TDD (with a 3:1 DL-to-UL ratio) becomes a large part of the proportion of the overall mix
  - In this case, extra spectrum is needed to satisfy the UL requirement in addition to the DL requirement
  - Our modelling suggests this could add up to 30% to overall spectrum need

Total low and mid band spectrum need (MHz) to meet both the DL and UL requirement

DL and UL total (including baseline) mid-bands spectrum need [MHz]

City	Popn density per km^2	Base Line Total MHz	Activity factor 10% High bands offload			Activity factor 15% High bands offload			Activity factor 20% High bands offload			Activity factor 25% High bands offload		
			30%	20%	10%	35%	25%	15%	40%	30%	20%	45%	35%	25%
Amsterdam	8,386	1,125	940	970	1010	1010	1130	1260	1150	1320	1480	1260	1460	1660
Amman	11,930	1,235	1130	1230	1350	1380	1550	1720	1580	1810	2040	1720	2010	2300
Riyadh	15,000	1,315	1290	1430	1580	1610	1830	2050	1870	2160	2450	2050	2410	2770
Jakarta	17,439	1,010	1370	1540	1710	1750	2000	2260	2040	2380	2720	2260	2680	3100
Paris	18,400	1,125	1410	1590	1770	1810	2080	2350	2120	2480	2830	2350	2790	3230
Cairo	18,934	790	1400	1580	1760	1810	2080	2360	2130	2500	2860	2360	2820	3270
Sao Paulo	21,542	1,110	1620	1830	2040	2090	2410	2720	2460	2870	3290	2720	3240	3760
Mumbai	24,773	725	1610	1850	2090	2150	2510	2870	2570	3050	3530	2870	3470	4070
Hong Kong	25,327	1,075	1730	1980	2220	2280	2650	3020	2710	3200	3690	3020	3630	4240
Lagos	30,968	810	2140	2440	2740	2810	3260	3710	3340	3940	4540	3710	4460	5210

Spectrum need	< 1225 MHz	1225 - 1925 MHz	1925 - 2725 MHz	2725 - 3225 MHz	> 3225 MHz
	Currently available in most of ITU Region 1[1]	Plus: 700 MHz potentially available in Upper 6GHz (see Ch.4)	Plus: 775MHz potentially available at 7.1-8.4GHz (see Ch.4)	Plus: potential extra 500 MHz at 7.1-8.4GHz outside Europe	Close to the limit within current sub-10GHz pipeline[2]

[1] Albeit this quantum may not yet have been fully allocated to mobile operators in all markets and may vary slightly across countries. This figure includes 100 MHz at 2.3GHz [2] This figure does not include a potential 70-80 MHz (UL plus DL) at 600 MHz that may be released in future, albeit the contribution to capacity (per MHz) from this band will likely be limited due to MIMO constraints.

Estimated MHz needed to meet the IMT 2000 data-speed requirements

Upper 6 GHz spectrum may be sufficient to meet 5G speed requirements in some countries until 2030, but additional mid band will be needed in others – and to support 6G requirements from 2030 onwards.

Our estimated ranges are premised on Activity Factors likely being higher in countries with higher incomes, and higher % offload levels likely where Activity Factors are high

Range parameters applied to different Word Bank Income Groups:

World Bank grouping:	Lower-bound based on:	Upper-bound based on:
High Income countries	**20%** Activity Factor with maximum **30%** offload	**25%** Activity Factor with minimum **35%** offload
Upper Middle Income	**15%** Activity Factor with maximum **25%** offload	**20%** Activity Factor with minimum **30%** offload
Lower Middle Income	**10%** Activity Factor with maximum **20%** offload	**15%** Activity Factor with minimum **25%** offload

Resulting spectrum need ranges:

Total DL plus UL need	Income	Lower-bound	Upper-bound	Average	Observations
Amsterdam	High	1,260 MHz	1,480 MHz	1,370 MHz	Likely achievable with extra U6G spectrum
Amman	Upper Middle	1,550 MHz	1,810 MHz	1,680 MHz	Likely achievable with extra U6G spectrum
Riyadh	High	2,050 MHz	2,450 MHz	2,250 MHz	Likely need U6G plus extra 7.1-8.4GHz
Jakarta	Upper Middle	2,000 MHz	2,380 MHz	2,190 MHz	Likely need U6G plus extra 7.1-8.4GHz
Paris	High	2,350 MHz	2,830 MHz	2,590 MHz	Likely need U6G plus extra 7.1-8.4GHz
Cairo	Lower Middle	1,580 MHz	2,080 MHz	1,830 MHz	Likely achievable with extra U6G spectrum
Sao Paulo	Upper Middle	2,410 MHz	2,870 MHz	2,640 MHz	Likely need U6G plus extra 7.1-8.4GHz
Mumbai	Lower Middle	1,850 MHz	2,510 MHz	2,180 MHz	Likely need U6G plus extra 7.1-8.4GHz
Hong Kong	High	3,020 MHz	3,690 MHz	3,355 MHz	U6G plus 7.1-8.4GHz may be insufficient[1]
Lagos	Lower Middle	2,440 MHz	3,260 MHz	2,850 MHz	Likely need U6G plus extra 7.1-8.4GHz

[1] Hong Kong is an outlier within our analysis. 3,225 MHz is the approximate limit of low and mid band within our identified pipeline for most regions, which would be ~130 MHz short of our central estimate of spectrum need for Hong Kong up to 2030.

Relationship between total spectrum bandwidth and the rural FWA opportunity

Adding upper mid bands spectrum to meet the 5G data-speed requirements would also improve the economics of FWA, meaning that it can be a long-term solution for rural broadband connectivity.

The FWA business case is highly dependent on the number of connections that can be supported per cell tower, which is a function of the data rate that must be delivered and, crucially, the amount of spectrum used at a cell tower

FWA covered homes per site model

Required data rate per FWA connection	Concurrent use (activity factor)	Amount of spectrum deployed on cell tower	→ Supported number of connections per cell tower
100 Mbit/s 150 Mbit/s 300 Mbit/s 1 Gbit/s	50%	Base line + 1,000 MHz + 2,000 MHz	

Results: FWA households supported depending on speed and spectrum[1]

Households supported per 5G FWA cell tower	100 Mbit/s	150 Mbit/s	300 Mbit/s	1Gbit/s
Baseline (400 MHz)	90	60	30	9
Baseline + 1GHz additional	315	210	105	32
Baseline + 2GHz additional	540	360	180	54

Note: The baseline is only 400 MHz of upper mid bands spectrum because we assume that low bands and lower mid bands are required for mobile capacity, i.e. not available for FWA.

- These calculations show that FWA can be used to cover isolated households (e.g. farms)
- More mid bands spectrum for rural FWA would significantly improve the business case for operators and will reduce or may even eliminate the need for rural broadband subsidies
- Importantly, the higher the capacity required the more critical mmWave spectrum availability becomes (in addition to upper mid bands spectrum)

Key assumptions

- Spectral efficiency of 5 bit/Hz
  - Assuming that outdoor customer premises equipment (CPE) result in an uplift to spectral efficiency
  - But that 16x16 MIMO (rather than 64x64) is used in rural environment
- A higher activity factor of 50% compared to 10-25% for mobile
  - Because fixed broadband usage likely to remain higher than eMBB usage
- Radio propagation in the range of 3.5 to 7GHz is not a limiting factor when assessing number of households which could be covered with 100 Mbit/s
  - Even with a cell radius of only 2 km, the area covered/site would be 12.6 km^2
  - Even if we assume a household density of only 50 per km2, the area covered by a single site would include 628 households (which is consistent with the number of households that would be served by a single site)

[1] *Taken from our earlier report 'Mobile Services, Spectrum and Network Evolution to 2025' (March 2021). This aligns with our June 2021 study for the GSMA.(ibid), spanning the 2025-2030 time frame.*

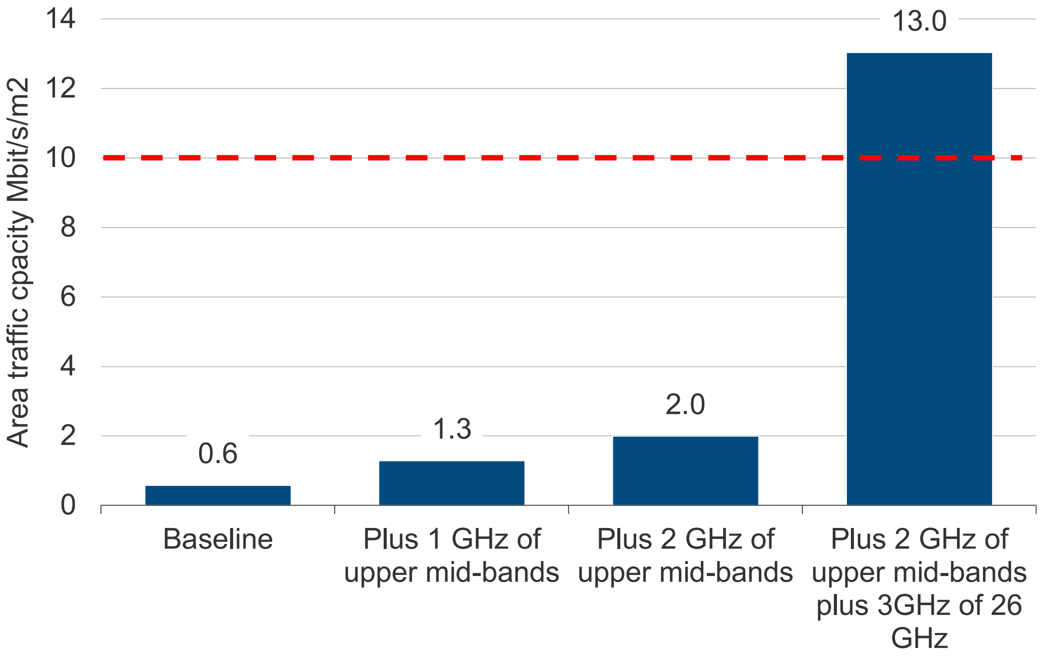
Total MHz needed to meet the 10Mbps/m² requirement

High bands (mmWaves) are required to deliver the required 5G area traffic capacity of 10 Mbps/m² in very high traffic density areas.

The ITU IMT-2000 requirements also specify a need to provide 10Mbps per square metre of capacity in areas with exceptionally high traffic densities

- These areas may include the busiest parts of cities, but also locations out of cities such as sports stadiums
- This requirement can only be met with mmWave spectrum, and with denser networks than assumed on the previous analysis

Spectrum and area traffic capacity[1]



Key assumptions

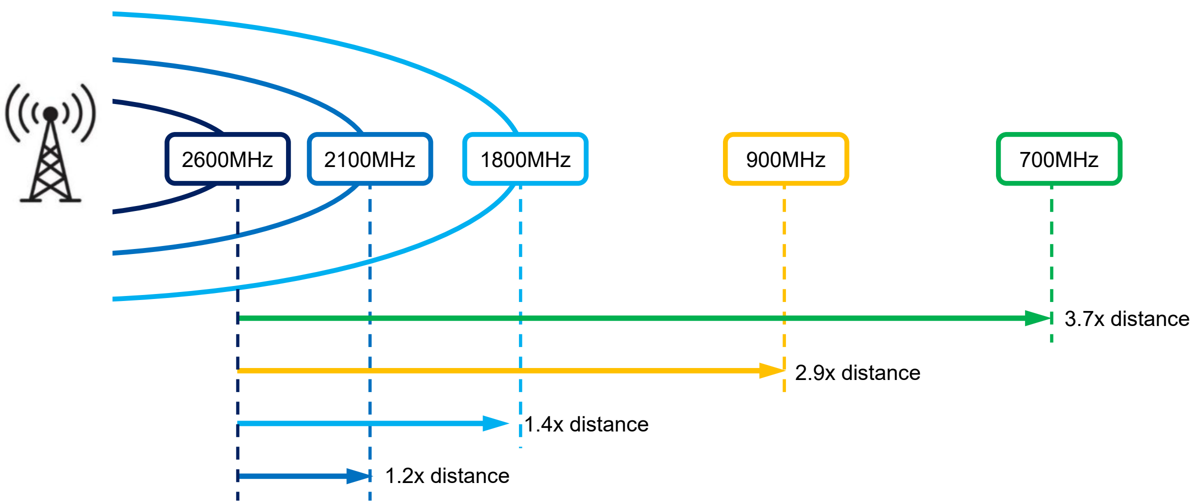
- Very dense network to meet the high traffic density
- Low and mid bands deployed on macro sites with a 100-metre site radius
- High bands deployed on a pico-site network with 20 metre cell radius
- As shown, low and upper mid band spectrum is not sufficient to meet the 10Mbit/s/m² traffic density requirement

[1] *Taken from our earlier report 'Mobile Services, Spectrum and Network Evolution to 2025' (March 2021). These results are independent of the time-frame under consideration. The baseline is just above 1GHz of low and mid band spectrum, and we consider alternative scenarios comprising th baseline plus 1GHz mid band, baseline plus 2GHz mid band and baseline plus 2Ghz mid band plus 3GHz in high band (mmWaves).*

low band spectrum need for coverage quality (1)

Superior propagation characteristics of low band spectrum benefit wide area and deep indoor coverage.

low bands (sub-1 GHZ) propagate further and deeper indoor than mid- and high band spectrum



Based on typical cell-radiuses, one would need ~14x the number of sites to cover an area with 2600 MHz spectrum versus with 700 MHz[1]

(Deep) indoor coverage quality is also far higher with low band spectrum, due to its lower 'path loss' (~18dB gain with 700 MHz versus 2600 MHz)

More low band spectrum is needed for mobile to boost cell edge capacity cost-effectively

- The burden on site capacity is far greater at the 'cell edge' (deep indoors, or at greater distances from the nearest radio site[2])
- As overall traffic increases, more capacity needs to be delivered to these locations to meet demand at acceptable levels of quality

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

[1] Cell coverage area is related to the square of the cell radius. The area covered by a 700 MHz site is around 3.7^2 = 13.7x greater than that for a 2600 MHz site.

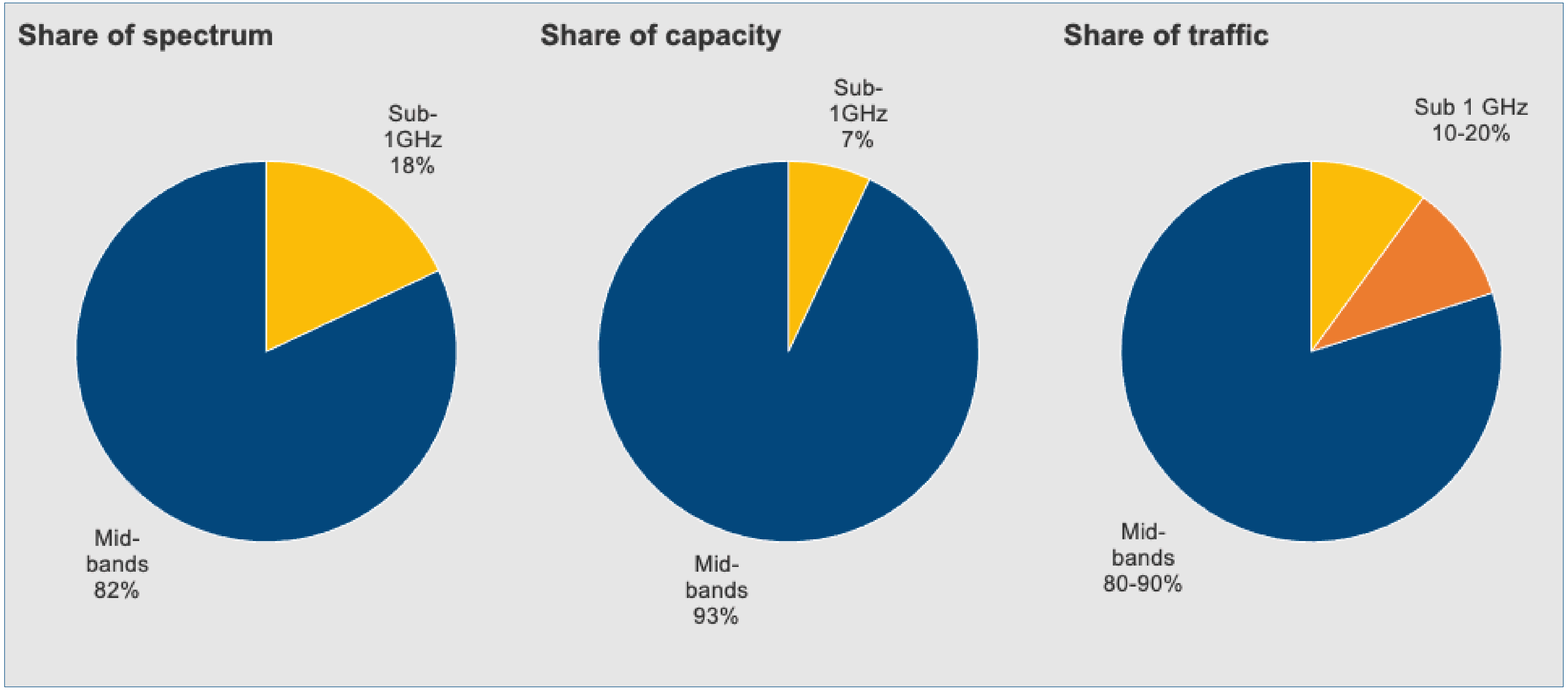
[1] Most non-urban usage in rural areas, where site density is lower, will be further away from the centre of mobile radio cells.

Low band spectrum need for coverage quality (2)

Low bands carry a disproportionate % of total traffic relative to the % of total site capacity provided by these.

Low band spectrum is scarce, and since there is less of an uplift potential from MIMO[1], its contribution to network capacity is limited – yet a significant proportion of total demand cannot be addressed with higher bands

- While low band typically accounts for ~18% of operators' spectrum holdings beneath 6 GHz, it typically contributes only 7% to total site capacity delivered by low, mid- and higher mid bands combined
- In urban areas, however, sub-1 GHz bands typically carry 10-20% of all traffic[2]



Accordingly, low bands are typically the most congested – and because a significant proportion of demand relies exclusively on sub-1 GHZ spectrum for connectivity, additional low band spectrum would be of high value both to society and to operators

[1] *See Chapter 2: higher-order MIMO implementations in sub-1 GHZ are more restricted due to the larger antennas needed in these bands.*
[2] *Source: 'IMT spectrum demand – Estimating the mid band spectrum needs in the 2025-2030 time frame', a Coleago report for the GSMA (June 2021)..As outlined in Ch.2, low bands carried around 30% of 4G traffic across a sample of 5 European markets (based on Tutela data, 2020).*

Low band spectrum need for coverage quality (3)

600 MHz represents an essential resource to relieve low band congestion and to drive improved performance.

Further awards to mobile in the 600 MHz band could increase download speed experience by up to 50%[1]

Region 1 – DL spectrum (MHz)	Case A	Case B
900 FDD	35	35
800 FDD	30	30
700 FDD	30	30
Current total	95	95
Potential 600	35	40
Potential total	130	135
Increase	37%	42%

Region 2 (LatAm) & 3 (APAC) – DL MHz	Case A	Case 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%

Region 2 North America – DL MHz	Case A	Case B
850 FDD	25	25
700 FDD + SDL	45	45
600 FDD	35	35
Current total	105	105
Potential extra 600 spectrum	15	30
Potential total	120	135
Increase	14%	29%

Potential increase in sub-1 GHZ bandwidth from 600 MHz:

- ITU Region 1: up to +42%
- ITU Region 2, Latam and APAC: up to +50%
- ITU Region 2, North America: up to + 29%

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

- Accordingly, experienced data-usage speeds could be increased by up to 50% (Latam and APAC) if 40 MHz is awarded in 600 MHz

In addition to improved performance, extra low band spectrum would provide extra cost-efficiency

- With an additional 2x10 MHz, 21% fewer cell sites would be required to cover the same area with a 30Mbps cell edge download speed
- With an additional 2x20 MHz, 33% fewer sites are required
- Lower network costs would benefit both society and operators – on the assumption that a proportion of savings would be passed on to consumers

As set out in Chapter 4, the global ecosystem for 600 MHz is growing rapidly, further underscoring the importance of this band for mobile

[1] *Insights in this slide obtained from Based on our 'IMT spectrum demand' report (ibid).*

Summary: low, mid band and mmWave spectrum need

Bandwidth shortfalls caused by a failure to release sufficient IMT-designated spectrum could result in substantial socio-economic harm.

Spectrum need to meet the 5G speed experience requirements

- To meet the 100Mbps DL plus the 50Mbps UL requirement in cities with 8000 or more inhabitants per square km, we estimate total low and mid band need ranging between 1,260 and 3,690 MHz (combined uplink plus downlink bandwidth)[1]

	Minimum estimate	Maximum estimate	
High income cities	1,260 MHz	3,690 MHz	Highest: Hong Kong
Upper middle income cities	1,020 MHz	2,870 MHz	Highest: Sao Paulo
Lower middle income cities	1,320 MHz	3,260 MHz	Highest: Lagos

- Upper 6GHz spectrum may be sufficient to meet 5G speed-requirements in some countries until 2030, but additional mid band will be needed in others – and to support 6G requirements from 2030 onwards
- Where the estimated demand exceed the (future) supply of low and mid band frequencies, the shortfall would entail either:
  - A failure to meet the IMT-2020 Requirements in exceptionally concentrated population areas; or
  - Costly measures to overcome the shortfall, including higher than assumed network densification and/or deployment of technology enhancements that deliver significantly higher spectral efficiency gains than projected

high band spectrum need (mmWave)

- Assuming a total of ~3GHz in low and mid bands, up to 3 GHz in mmWaves would be needed to meet the 10Mbps/sq.metre area-capacity need in very high traffic-density areas – this would likely also suffice for the % offload assumed in our wider modelling

low band spectrum need (sub-1 GHz)

- low band is invariably the most congested, and as demand grows, pressure on (indoor) cell edge capacity is likely to increase
- Yet sub-1 GHZ spectrum is very scarce, and it is unlikely that supply in this category can be increased by more than 50%
- Thus, future demand is likely to exceed supply – releasing the maximum possible amount of 600 MHz to mobile operators by 2030 should be a high priority for policymakers, to avoid undue degradation in the (indoor) quality of mobile services in the mid-term

[1] From on our 'IMT spectrum demand' report (ibid) – these results include data-points across a sample of 35 cities

Managing the transition to 5G advanced, readying for 6G

Optimising spectrum use while ensuring legacy-tech demand is addressed

6

Key imperative: ensuring demand across all technologies is addressed

Many 4G networks are currently overloaded, while available 5G capacity is still under-utilised.

The experience of 4G customers today will define operator brand perceptions for many years.

Hence operators need to take account of legacy 4G capacity needs in their investment plans.

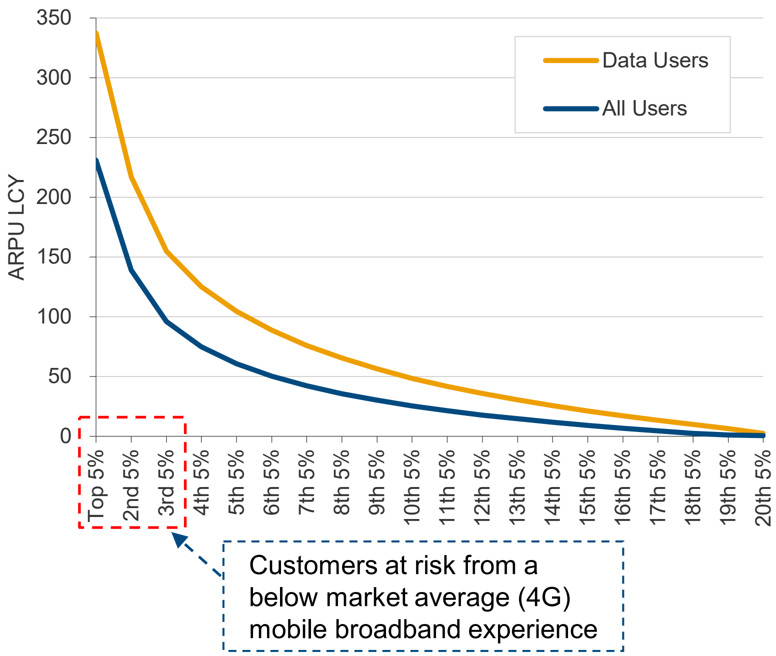
Global 4G capacity needs are set to increase by ~37% between 2022-2027, and many 4G networks (especially in South-East Asia) are overloaded, while available 5G capacity still lies idle – the transition from 4G to 5G therefore requires careful management

- Operators need to include substantial 4G capacity expansion in their investment plans, and not just focus on 5G roll-out

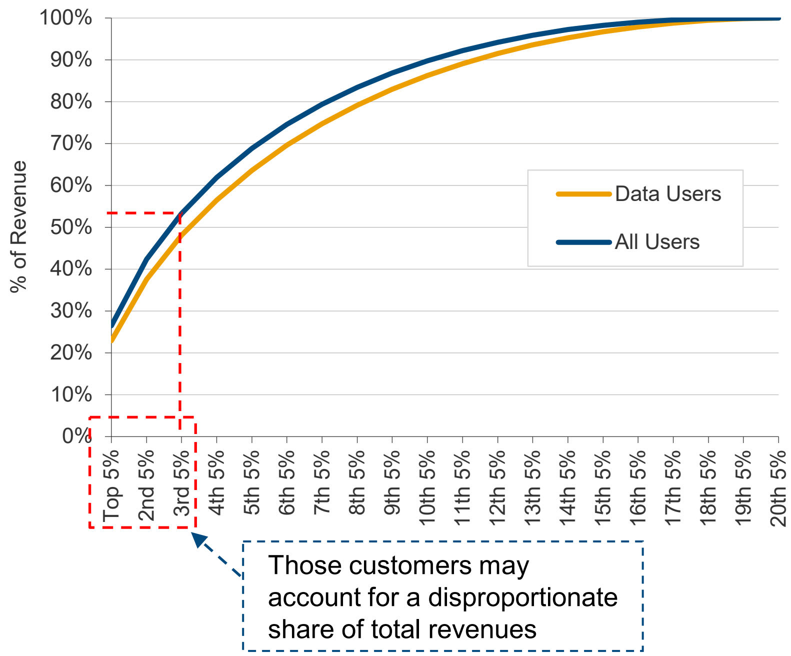
The experience of 4G customers today will determine their perception of operator brands for many years

- Even if the 5G network is fantastic, an underserved 4G customer may switch to a rival network before (or when) upgrading to 5G
- Higher value customers tend to be more sensitive to data experience – lack of 4G capacity may have a disproportionate impact on revenues

Typical ARPU distribution by 5 percentiles



Typical revenue distribution by 5 percentiles



The investment challenge: need to ensure good 5G availability[2] to encourage faster customer migration to 5G – while providing sufficient 4G capacity to address legacy-technology demand

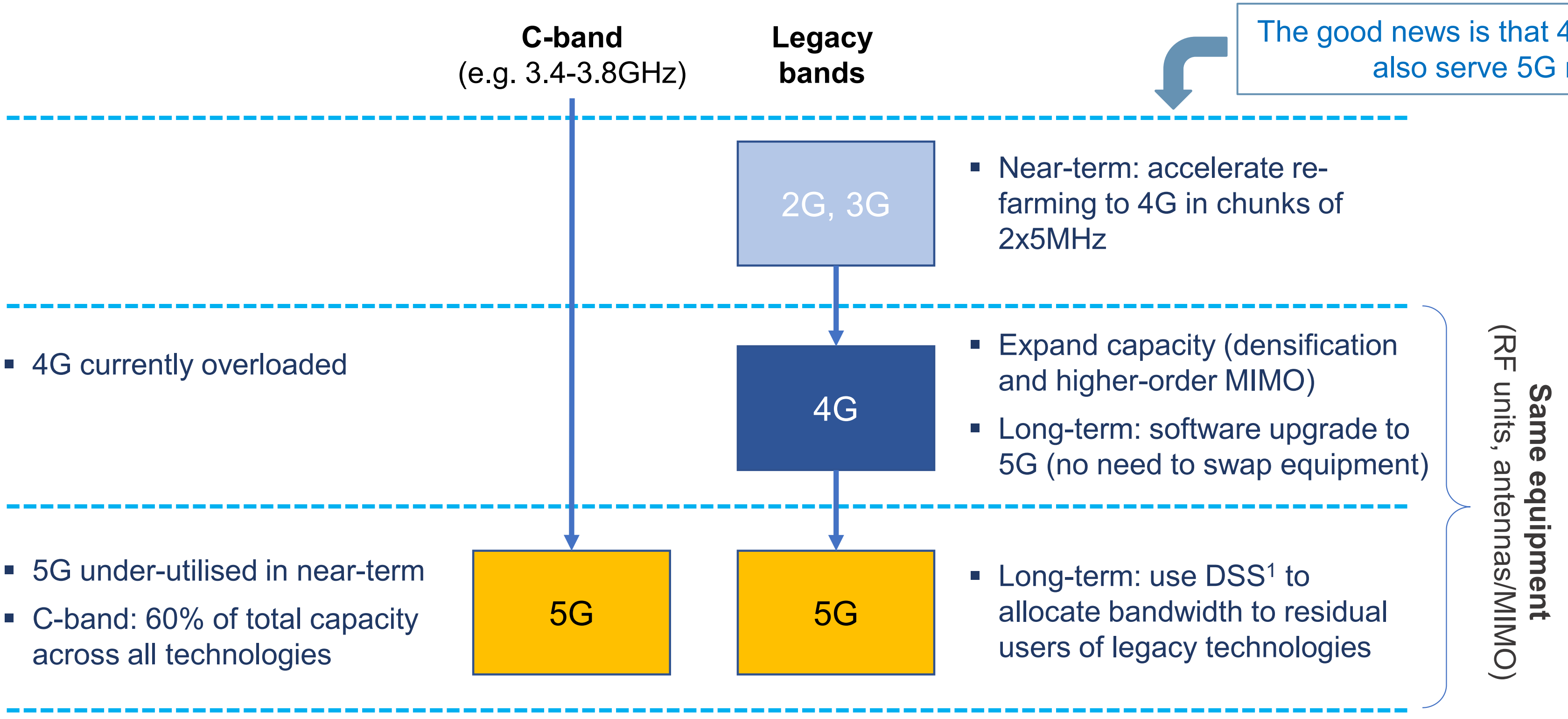
[1] *Based on our analysis in Chapter 1.*
[2] *Availability means both coverage and capacity. Allocating low band resources such as 700 MHz to 5G could mean less capacity for 4G (while higher mid band 5G is underutilised); but without low band 5G resources, 5G would be (relatively) less attractive due to weaker 5G coverage.*

Spectrum refarming schedule

With the exception of C-band deployment, one cannot strictly speak of 4G versus 5G investments.

For example, 700 MHz is a 5G band in ITU Region 1, but may be used for 4G low band capacity using DSS[1,2].

The good news is that 4G investments today will also serve 5G needs tomorrow



Projected legacy-traffic peak:

- N.America: 2022
- W.Europe: 2023
- N.E.Asia: 2024
- After 2026 in all other regions

5G equipment (RF units as well as MIMO antenna-systems) supports both 5G and legacy technologies, so expanding 4G capacity with 5G-ready infrastructure does not entail deployment of assets with a curtailed economic life (i.e. no 'stranded investments')

- Dynamic spectrum sharing (DSS) provides great flexibility in the allocation of bandwidth between 5G and legacy technologies: it is no longer necessary to re-farm spectrum in chunks of 2x5MHz across the network – once peak-legacy traffic is reached, DSS can be used to gradually shift capacity in legacy bands from 4G to 5G, allowing operators to closely match demand across each technology as time progresses
- Nevertheless, 5G remains more efficient, and operators have an incentive to rapidly migrate customers to 5G to make best use of the available resources – basic connectivity over 5G should not be more expensive than over 4G, as this could hinder upgrades to 5G
- Another key factor in 5G migration is device availability and cost (discussed in later slides)

[1] DSS: Dynamic Spectrum Sharing.

[2] Strong existing global device support for 700 MHz in 4G – so 700 MHz can be used to provide 5G coverage layer as well as extra 4G capacity.

2G and 3G switch-off

2G switch-off is generally favoured in Asia Pacific, while 3G is being shut down first in much of Europe.

Legacy sunset strategies vary internationally – with either 2G or 3G already or imminently closed in many markets[1]

	Country / operator	2G switch-off	3G switch-off
High-income markets	United States (T-Mobile)	2024	2022
	France	2025-2026	2028-2029
	Germany (Vodafone)	2025	2021
	UK, Finland, Sweden	2025	2023-2025
	Spain	2025-2030	2025
	Belgium (Orange)	2030	2025
	Saudi Arabia		2022
	UAE	2022	
	Australia, New Zealand	2018-2020	2024
	Japan	2011-2012	2022-2026
Emerging Markets	Argentina (Personal)		2023
	South Africa (MTN, Vodacom)	2024	2025
	Malaysia		2021
	Thailand (dtac)	2015	2025
	Indonesia (Axiata)	2022	2022
	India (Bharti)	2023	2020
	Pakistan (Telenor)	2025	2025
	Bangladesh (Grameenphone)	2025	2026

2G and 3G are spectrally inefficient technologies, however refarming to 4G and 5G has been hindered by legacy handsets, including installed M2M devices that are costly to replace.

By 2030, however, 2G and 3G will be obsolete.

[1] *2G and 3G sunset timings sourced from Onomondo, May 2022.*

Preparing for 6G

Deploying and exploiting the benefits of 5G Advanced is a first, essential step towards 6G.

Managing the transition to 6G is not just about networks – it is largely a question of strategic mindset and commercial positioning

Image courtesy of Nokia

- 5G Advanced is a key precursor to 6G – it contains key technology components that form precursors to essential elements of 6G
- For longer-term positioning, operators should actively pursue use-cases such as XR, industrial applications including key IoT categories that require enhanced reliability, accurate positioning and/or low power consumption – as well as the delivery of deliver 5Gbps peak speeds[1], a cross mobile-generational step change in user experience

Image courtesy of Nokia

[1] A range of carrier-aggregation configurations that could enable this are discussed towards the end of Chapter 3 (see 'Key Priorities 2023-2030: High-income countries')..

7

Operator business case for additional spectrum

Quantifying spectrum value from the industry's perspective

Key spectrum acquisition considerations

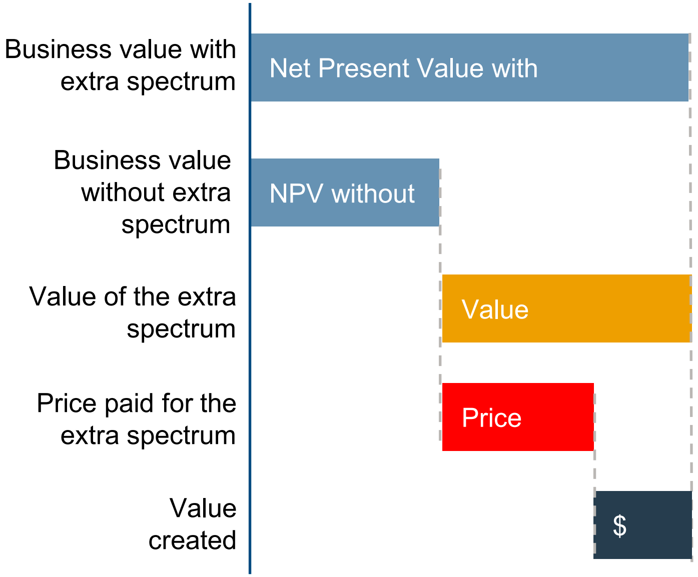
Shareholder value is created from spectrum acquisition if operators pay less for spectrum than it is worth to them.

In contrast with the societal perspective, operators express spectrum demand in terms of what they are willing to pay for it. For them, the drivers of spectrum value include:

- Cost avoidance potential: it is generally cheaper to extend network capacity by deploying additional spectrum than by densifying the network (subject to the cost of spectrum licenses)
- Value of the potential market share gains or losses associated with different spectrum portfolios
- Scope to address incremental revenue streams with additional spectrum

Spectrum acquisition is economically justified for operators if its value exceeds the cost, albeit operators may be subject to fixed budget constraints

- Capital constraints may prevent them from acquiring spectrum that they value above costs, if licence prices are high – but this does not affect how they *value* the licences themselves



Value is created as long as acquiring and deploying new spectrum is cheaper per Mbit/s of extra capacity than all alternatives (such as network densification and capacity-enhancements in other bands).

If opportunities to secure new sites (macros or small cells) is limited, however, new spectrum may be the only route to increase network capacity to the required levels.

Case study: India 700 MHz auctions

- 2016 auction: 700 MHz left unsold due to excessive reserve prices
- March 2021 multiband auction: 700 MHz still left unsold
  - Still too expensive, despite a 43% reduction in prices from 2016
- Walking away from spectrum is rational if prices exceed value

Everyone loses out as a result:

1. Less efficient network capacity expansion for operators
2. Scarce national resources left idle for over 5 years
3. Foregone consumer benefits from spectrum deployment in a key coverage band (lost opportunity to improve indoor and wide area coverage quality)
4. Indirect impact on economic development (see next slides)

Network cost avoidance

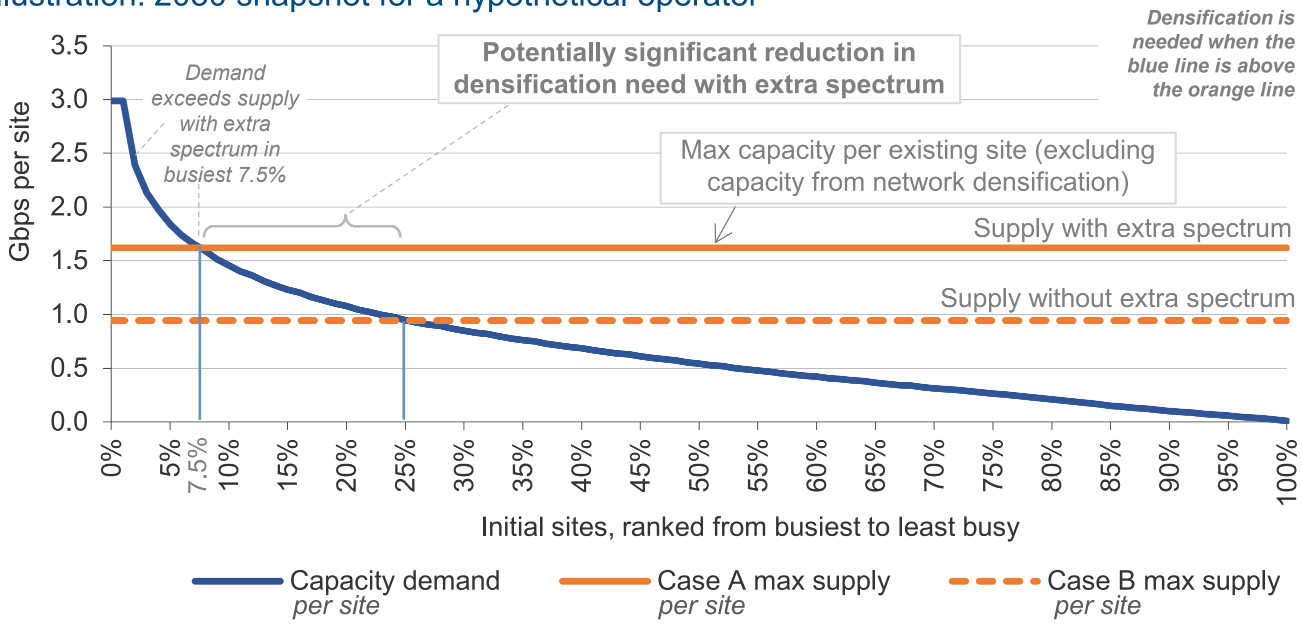
Deploying additional spectrum bandwidth reduces the need for site densification.

The net cost savings from this can be substantial, driving high spectrum valuations.

Valuing spectrum using the 'network cost avoidance' method involves assuming a fixed evolution of traffic in all spectrum scenarios, and comparing total network costs across these

- The difference in the net present value (NPV) of network costs between a 'Case A' (assuming additional spectrum) and a 'Case B' (reflecting current spectrum holdings) yields the 'cost-avoidance' value of the additional spectrum licences

Illustration: 2030 snapshot for a hypothetical operator



Assumptions applied in the illustration:

- The operator has a constant 30% share within a country with 30 million inhabitants, and starts with 10,000 macro sites
- Traffic grows **4x** to 80GB per capita per month in 2030 (in line with global TDI, Ch.1)
- Typical busy-hour (BH) traffic profile: 10% in the BH, 90% downlink, and ~50% of BH traffic carried in the top 20% busiest sites
- We use the same spectral efficiency factors as in Ch.5, but ignore speed targets[1]
- Case A: 55 MHz in sub-1 GHZ bands, 55 MHz in lower mid bands (FDD) and 100 MHz at 3.5GHz (TDD), yielding a total of **210 MHz** (uplink plus downlink)
- Case B: same as Case A but with 50 MHz less at 3.5GHz, yielding a total of **160 MHz**

- In Case A in our illustration, there is sufficient bandwidth to cover 2030 demand for capacity in the lower 92.5% of sites, meaning site densification is needed within the first 7.5% (see graphic above) – while in Case B, densification is needed across the top 25%
- This already accounts for a difference of 1,750 sites (**17.5%** of the initial site count) – however, more than one densification layer is needed in the busiest parts of the network, leading to a larger overall delta in macro sites and/or small cells between Cases A and B

The net cost savings need to take account of the cost of deploying the extra spectrum – in our example, the latter is negligible as the extra spectrum in Case A is within an existing band (i.e. the costs of deploying the band will already be reflected in Case B)

[1] *Including a 15% design margin and a 3:1 downlink v uplink ratio for TDD spectrum. For the illustration, we assume that demand for capacity across the network is driven by traffic alone (i.e. we ignore the speed experience targets discussed in Chapter 1).*

market share impact

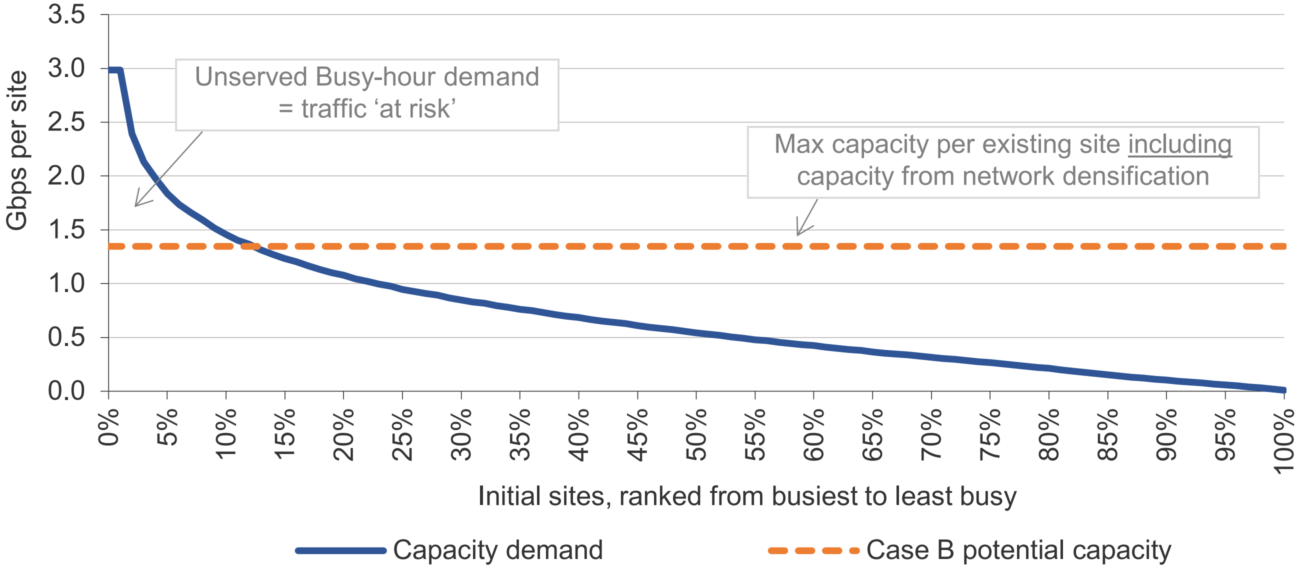
Differences in congestion levels across networks may impact on market shares.

There may be practical limits to network densification[1], meaning that it may not be possible to meet demand for capacity in certain spectrum scenarios – this is especially likely for low bands, which are the most congested (see next slide)

- If one cannot 'build' oneself out of congestion, a proportion of demand will be unmet
- All other things remaining equal, congestion is likely to drive customer churn – with customers, traffic and revenues moving from relatively more to relatively less congested networks, yielding a new market share equilibrium (in which relative congestion levels are more balanced across networks)

Expanding on the illustration in the previous slide:

- Suppose that no new macro sites can be deployed (due to a lack of site options – e.g. a ban on new macro sites by municipalities)
- Assume further that small cells can be deployed, but up to a limit of 60,000 (an average of maximum 6 small cells per initial macro site), and that each small cell provides 40Mbps of capacity
- In this scenario, the demand for capacity in 2030 can be met in Case A, but not in Case B



Scenario result: **~40%** of BH traffic unmet in Case B.

This could lead to a significant loss of market share for the operator if Case B were the outcome – driving a potentially large valuation for the 50 MHz under consideration, over and above the cost-avoidance component.

[1] A minimum inter-site distance needs to be maintained to manage interference. In addition, securing suitable site locations to deploy radio equipment may be difficult, restricting the scope for site densification in key areas.

Relative value of low and higher band spectrum

A significant proportion of demand can only be met with low band spectrum, while high band is needed where the demand is highly concentrated.

The value of low band spectrum is driven by its unique wide area and deep-indoor coverage reach

- 10-20% of total demand can only be addressed with low band spectrum (see Chapter 5)
- As overall traffic continues to grow, the pressure on cell edge capacity rises (assuming the % of indoor and wide area consumption persists) – which will likely lead to a deterioration in service quality, unless additional low band capacity can be delivered
- Accordingly, a low band spectrum shortfall relative to competitors could degrade an operator's competitive position, leading to a loss of market share (or a need to discount services to compensate for reduced overall quality of service)[1]
- Additional low band spectrum may also allow operators to target new revenues more cost-effectively, such as **rural FWA** and **IoT**

The total deployment capex and opex per MHz is higher for sub-1 GHZ spectrum (due to the typically narrower channels and larger antennas needed), leading to a higher cost per Mbps of capacity delivered per site – however, because this capacity cannot be substituted with higher bands, sub-1 GHZ spectrum is often valued at a significant premium[1]

- For example, 3.4x more was paid per MHz for 700 MHz than for 3.5GHz in the combined 2021 award in the UK

The prices of higher bands are depressed by their greater abundance

- For example, mmWave bands in the 24-29 GHz range (n257 and n258) each contain around 3 GHz of IMT bandwidth (7.5x more than in the 3.4-3.8 GHz range)
- Greater abundance reduces contention levels, decreasing average prices per MHz – the wide availability of potential substitutes also reduces actual valuations
- Because of their shorter transmission range, mmWave bands tend to be suitable in more limited cases
  - Areas in which demand is highly concentrated (such as dense urban or transit areas with high concentrations of people at busy times, and sports stadiums)
  - Fixed wireless access (FWA) where topography allows line-of-sight transmission over longer distances
- Nevertheless, additional higher mid band and new mmWave allocations may allow operators to target the new revenue streams discussed in Chapters 1 and 3

(1) More effectively address **FWA**, **critical IoT** and **network-slicing based private mobile networks**; (2) Enable **speed-based** and **quality-of-service based pricing**; (3) Better serve needs for **immersive and 3D applications** and **mobile cloud computing**

[1] *Note that low band densification is typically far more difficult in denser urban areas, so it is very difficult to mitigate low band insufficiency (and loss of indoor capacity) through extra network build – hence the value of low band spectrum is likely to include a market share impact component.*

Part III

Part III – Public Policy Perspective

Guidance and best practices for policymakers

Chapter 8	The importance of a thriving mobile sector
Chapter 9	Best practices in Spectrum Management and Pricing
Chapter 10	Policies to accelerate network expansion
Chapter 11	Concluding remarks

8

The importance of a thriving mobile sector

Impact on society

Widespread benefits of mobile

These days, it is hard to imagine what the world would look like without mobile communications.

If mobile networks were to disappear, the economy would suffer heavy losses in productivity and welfare.

There are very few parts of society and of the economy that are not touched by mobile communications. Mobile allows us to stay informed, drives the wheels of the economy, and keeps us entertained and safe.

C2C, B2B, B2C[1]

- Ubiquitous communications between private citizens, within businesses and with customers
- Instant transfer of information and knowledge – drives economic productivity and efficiency
- Increased participation in the knowledge economy, bridging the digital divide – for many, mobile is the sole access to the Internet
- Entertainment, gaming
- Massive source of welfare (consumer surplus), convenience and safety

IoT, industrial and enterprise Metaverse

- Key driver of the 4th industrial revolution, yielding massive productivity gains (e.g. smart manufacturing)
- Unprecedented convenience (e.g. smart home, smart vehicles)
- Increased public and personal health and safety (e.g. smart health, emergency services and public protection, smart vehicles)
- Energy efficiency, reduced waste and pollution (e.g. smart buildings, smart agriculture, smart vehicles)

The mobile industry is a key industry with powerful externalities – policy makers need to treat it with care

Mobile externalities → **Very large *absolute* contribution to the economy** – **A plus to consumer welfare** → **Large *marginal* impact on economic development** – **A plus to consumer welfare**

[1] C2C: Consumer-to-consumer communications; B2B: Business-to-business; B2C: Business-to-consumer.
M2M: Machine to machine

Very large absolute contribution to the economy

The bulk of value created by mobile accrues to society rather than to the operators.

Overtaxing the industry (e.g. though high spectrum fees) threatens the wider societal value.

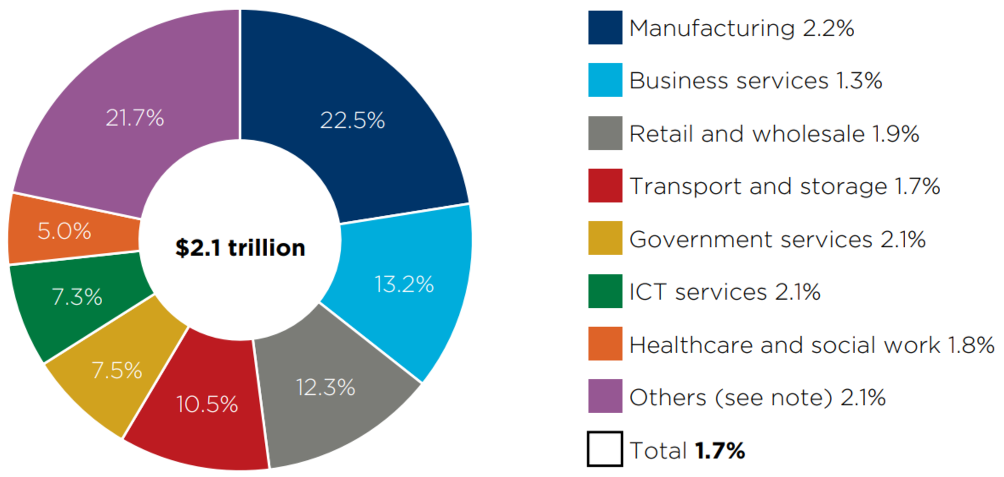
GSMA: by 2030, the mobile communications will contribute $6 trillion in economic value added[1]

- **4.7%** of 2030 GDP (at 2023 prices)
- This represents a **6.2x** multiple over the GSMA's global industry revenue projection for 2030

5G is projected to boost global GDP by $1.3 to $2.1 trillion by 2030

- PwC projects a **$1.3 trillion** boost from 5G[2]
- Oxford Economics project a **$1.3 trillion** boost for 5G-enabled technologies in mid band plus a further **$800 billion** boost those using mmWave spectrum by 2030[3]

Sectoral distribution of global productivity-enabled GDP gains from full 5G rollout in 2030



Figures in the legend show growth in sector economic output associated with 5G-enabled technologies.

Graphic courtesy of Oxford Economics

[1] *Source: GSMA, 2023. Proportion of GDP based on real GDP at 2023 prices. Economic Value Added (EVA); the surplus above the cost of capital enabled by mobile communications.* [2] *Source: PwC, 'The global economic impact of 5G' (2021)* [3] *Source: Oxford Economics, 'The global economic potential of 5G-enabled technologies', a study for Qualcomm, March 2023.*

Large marginal impact on economic development[1]

Both older and more recent econometric studies show that moderate changes in mobile adoption and data usage have a large impact on productivity and GDP growth.

Each new mobile generation introduces new capabilities driving further economic growth – this is highly likely to persist in the 5G era[1].

In addition to the very large absolute contributions from mobile communications, increased adoption and usage also has a large marginal impact on economic growth

Studies based on 2/3G era data

1) Qiang and Risotto (World Bank, 2009): **10 pp** increase in penetration increases GDP growth by **0.60 pp** in high-income countries and **0.81 pp** in low- middle income economies

2) Deloitte (2012, 2013): **10%** higher mobile penetration = **4.2 pp** increase in Total Factor Productivity (TFP) in the long run | **10 pp** increase in 3G penetration = **0.15 pp** increase in GDP, with 1GB AUPU driving **0.6 pp** in GDP growth

3) Chalmers University of Technology (2012): Doubling (average) broadband speed = **0.3%** extra GDP growth

Studies spanning the 4G era

4) Capital Economics (UK study for EE, 2014): eventual productivity gains between **0.5%** and **0.7%** of GDP from introduction of 4G

5) Goodridge *et al* (Imperial College Business School, 2017): **10%** increase in MBB adoption = **0.6-2.8%** increase in GDP

6) Bahia *et al* (GSMA, 2020): **10%** increase in overall mobile adoption = **0.4-0.8%** increase in GDP per capita, while a **10%** increase in MBB adoption drives further gains of **0.1-0.7%**

10% extra population coverage could thus raise GDP per capita by up to 1.5% – A gain in the order of total mobile industry revenues (~1% GDP)! This underscores the socio-economic importance of overcoming the current 13% coverage gap (see Ch.1)

Impact of IoT

7) Frontier Economics (2018): **10%** rise in M2M connections = annual increases of **0.7%** of GDP, **0.3%** in services Gross Value Added (GVA) and **0.9%** in industry GVA

8) Goodridge *et al* (2019): **10 pp** increase in the growth of IoT = **0.23 pp** increase in TFP

1) Based on 1980-2006 growth data from 120 countries; 2) Based on 1995-2010 data from 74 countries and 2008-2011 data from 93 countries; 3) Based on 2008-2010 data from the 34 OECD countries; 4) Based on 2002-2014 data from GSMAi; 5) Based on 2012-2015 data from 27 EU and OECD countries; 6) Based on 2000-2017 data from 160 countries; 7) Based on 2010-2017 data from 82 OECD and non-OECD countries

Economic development is highly sensitive to adoption and usage of mobile services

↓

Adoption and usage is sensitive to network coverage and capacity (investment) and to retail prices

↓

Mobile investment and retail prices are sensitive to the financial position of operators and their ROIC[2] prospects

↓

The financial position of operators and their ROIC prospects are heavily influenced by public policy

↓

Hence socio-economic development is highly sensitive to public policy towards mobile

Especially spectrum and pricing policy (discussed later)

[1] Note: econometric studies are based on historical data, mainly covering the 2G-4G eras. However, the positive economic impact is likely to persist (and may even be greater) in the 5G era. [2] ROIC: Return on Invested Capital. ROIC below the industry cost of capital (WACC) tends to discourage investment and may be unsustainable in the longer run (especially if the shortfall is severe and prospects of recovery are poor).

Impact on consumer welfare (in addition to GDP impact)

Far more spectrum is needed to meet future mobile data demand.

It follows that extra spectrum availability bears heavily on mobile adoption and use, hence on welfare and socio-economic development.

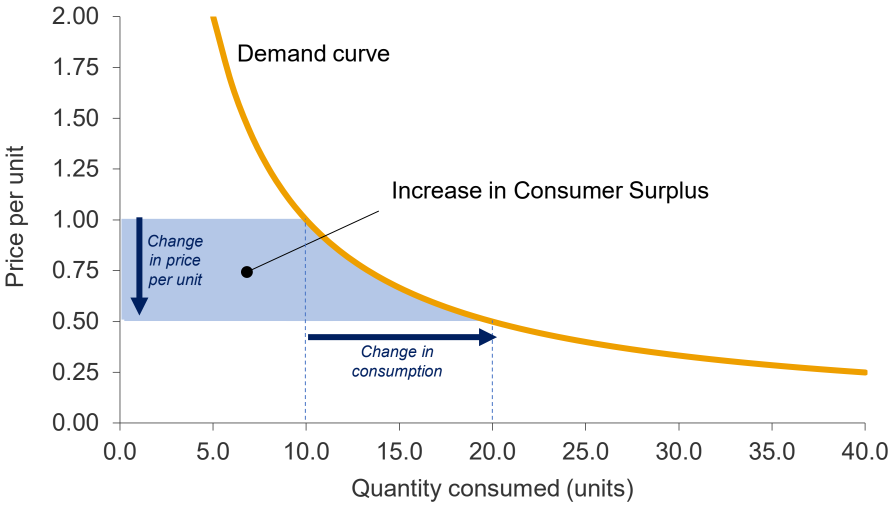
Mobile already yields very high levels of consumer welfare

- Consumer surplus (CS) in the US was estimated at $200 billion in 2009 vs ~$150 billion in annual mobile industry revenues[1]
- 2021 mobile data traffic ~140x 2010 levels in the US[2], with no real growth in spend – suggesting 2021 CS around 8x mobile revenues

Extra spectrum would boost welfare even further

- Broadly flat total mobile revenues per customer against a backdrop of steeply declining prices per unit of consumption suggests an isoelastic demand curve[3]
  - Halving of unit prices = doubling of usage per customer
- In these conditions, the increase in CS per user from a halving of effective prices per GB consumed is equal to 69% of the customer's total spend[4]

Impact of halving prices per unit on Consumer Surplus (CS)



Lowest (yet still very large) impact: Western Europe

- Projection (see Ch.1): 3.4x data usage multiple for 2030 v 2023, corresponding with a reduction in unit prices by ~2/3rds
- This entails extra CS of almost 1.2x total consumer spend on top of the unquestionably high existing CS from mobile consumption
- Moreover, this does not take further consumer welfare benefits from increased data-speeds into account

Highest impact: sub-Saharan Africa

- Projection (see Ch.1): 7x increase in data usage between 2023 and 2030
- Extra CS would be almost 2x total consumer spend
- Much of this extra welfare would be foregone if insufficient spectrum is made available to operators

Welfare cost of capacity constraints

- As outlined in Ch.1, network congestion suppresses an estimated 15% of total mobile data consumption globally
- This means that if there were no congestion, up to 18% (=1/0.85) more data would be consumed at current effective prices per GB

Eliminating network congestion could thus increase the total consumer welfare from mobile by up to 18% (almost a fifth)[5]. With CS around 8x total industry revenues, eliminating congestion could drive extra social gains in the order of **1.6x** total mobile spend

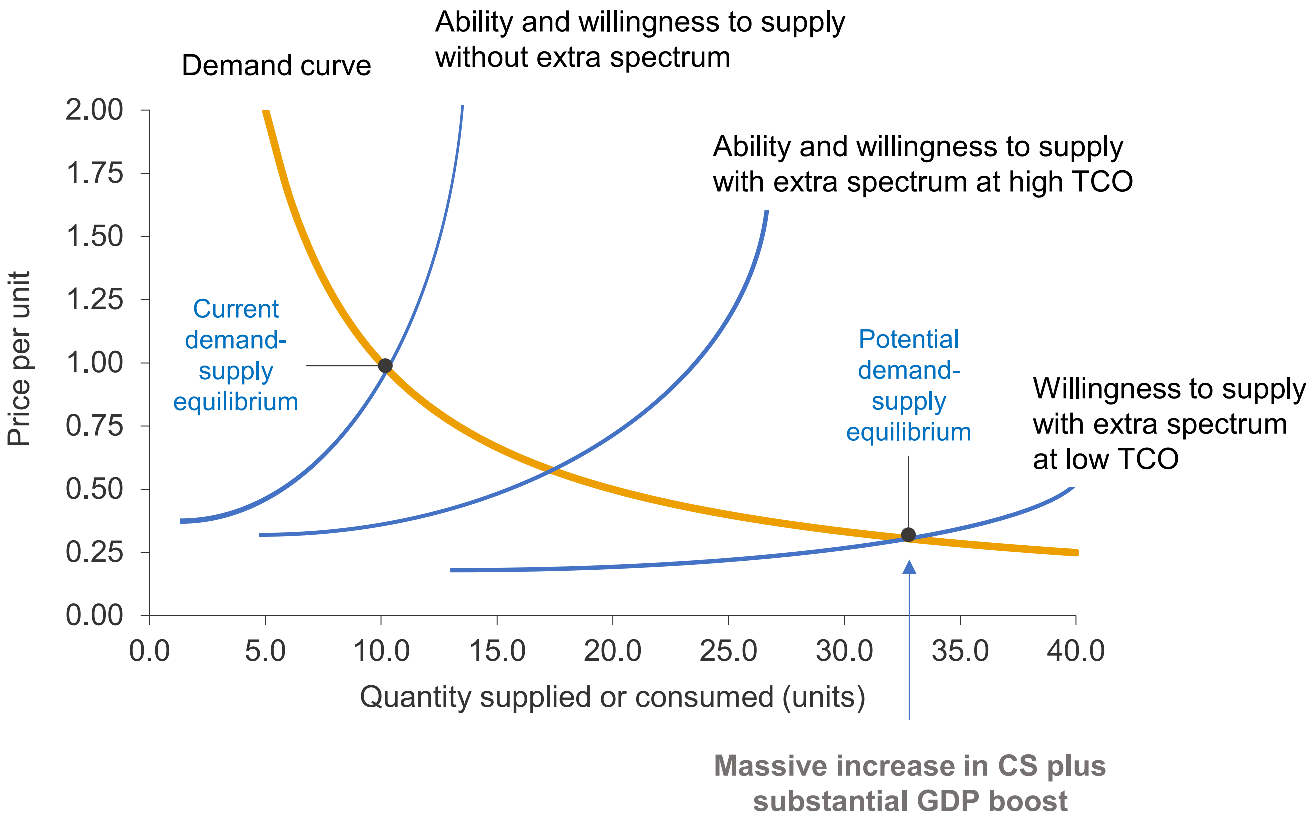
Extra spectrum is needed at reasonable prices to allow the capacity expansion needed for substantial increases in AUPU (and reductions in prices per GB)

[1] Hazlett , Munoz et al, 2012. [2] Source: Statistica, 2023. [3] Isoelastic curve: price elasticity coefficient of 1, implying constant revenues at all prices per unit of consumption. [4] The change in CS is given by the area of the blue section in the graph. As a % of revenues, the change in CS can be calculated as ln(1.00) – ln(0.50) = 69%. [5] Assuming the same % congestion applied historically.

Ensuring the socio-economic gains materialise

policymakers can ensure the socio-economic gains materialise by releasing as much spectrum as possible, as fast as possible and as cheaply as possible.

Impact of large spectrum allocation at low prices (illustrative)



In addition to significant welfare gains (CS), extra spectrum would drive GDP growth by enabling further adoption and use of mobile data

(as per previous slides)

The quantity of spectrum is important, but so is the price paid by operators

- Operator supply curves (willingness to supply as a function of price per unit) are affected by the scope to earn returns (ROIC) that match the cost of capital (WACC)
- Spectrum TCO[1] is a significant line-item in operator costs and has a significant impact on the income and capital requirements of operators – hence on their ROIC
- Policymakers have direct control over annual spectrum fees and the conditions on which spectrum is awarded (discussed in more detail later)

[1] *TCO: total (annualised) cost of ownership*

9

Best practices in Spectrum Management and Pricing

Protecting and enhancing the social gains from mobile communications

Public policy objectives

Sustainably better social outcomes should be the overriding object of public policy.

High industry costs impede investment and retail price erosion, harming socio-economic development.

Lower GDP growth also reduces government tax receipts – this may overshadow direct spectrum fee income.

Policy should target superior social outcomes rather than revenues extraction

Public policy objectives

a) Welfare generation (Consumer Surplus)
b) Higher digital participation
c) Drive growth in productivity, employment and GDP
d) Drive transfers from the industry to the state?

- 1. Efficient use of spectrum
  - 1.1 Efficient packaging of spectrum
  - 1.2 Efficient allocation of spectrum
  - 1.3 Interference coordination & coexistence
- 2. Sustainable competition
  - 2.1 Avoid excessive concentration of spectrum
  - 2.2. Reduce financial burden on operators
- 3. Investment and innovation
  - 3.1 Regulatory certainty
  - 3.2 Opportunity for industry to earn ROIC aligned to WACC

- **Wider mobile coverage**
- **Higher network capacity**
- **Lower retail prices**

=

- **Wider access to mobile**
- **Higher adoption of services**
- **Higher use of mobile**

=

- **Higher digital participation**
- **Higher consumer welfare (CS)**
- **Higher GDP, employment**

Finance Ministers often favour extracting higher spectrum licence fees – but these are counter-productive

- A higher financial on industry threatens investment and may lead to higher prices
  - Negative for economic growth and consumer welfare (see next slides)
  - Leading to lower tax receipts for State
- High spectrum fees threaten the sustainability of competition

Efficient use of spectrum should be a key objective

- Spectrum is a scarce national resource
- Need to balance maximisation of customers per MHz with ensuring market challengers can compete
  - Market leaders may value spectrum more highly, but concentration of bandwidth harms competition

Spectrum award mechanisms (1)

Prices paid for spectrum are heavily influenced by policy choices – e.g. annual fees, auction design and reserve prices.

The main spectrum auction formats are the SMRA and CCA.

Both have significant vulnerabilities that threaten allocation efficiency and may drive collective overpayment.

Auctions for the award of spectrum have become the norm, because they yield an objective allocation criterion, which is deemed fair to all candidates

- A perceived additional benefit is that competitive bidding may drive up spectrum revenue for the state – albeit this may not actually maximise social utility (discussed later)
- The main problem with auctions is that private valuations may not correspond with social value: operators may ascribe high values to spectrum for the wrong reasons
  - For example, spectrum becomes highly valuable if acquiring it forecloses or diminishes competition
  - Furthermore, the main spectrum auction formats each have their own vulnerabilities
  - Auctions may drive collective overpayments, harming investment and retail prices (discussed later)

Mechanism	Key features	Key advantages	Key disadvantages
Administered allocation	• Allocation and prices of available spectrum determined by regulator	• Remain in control of outcome (makes sense if there is an obviously efficient allocation)	• Subjective, may be deemed unfair if lots cannot be awarded equaly • Less suitable if there are prospective market entrants
SMRA auction[1]	• Participants bid on individual lots • Prices rise in each categories while demand > supply • Winners pay as bid (‘first price’)	• Simple and well-understood by regulators and operators • Works well when bidders constrained by hard budget limits	• Collective demand-moderation incentives (to minimise prices) • Exposure risk: win subset of target package at an unprofitable price
CCA auction[2]	• Participants bid on packages of lots (win whole package or nothing) • ‘2nd price rule’ (winners pay opportunity costs[3]) – i.e. prices paid determined by losing bids of rivals	• No risk of winning an unwanted subset of a target package • Truthful bid incentives (promote value-maximising allocation)	• Can yield very inefficient outcomes when bidders have fixed budgets • Asymmetric pricing (winners can pay more for less than rivals) – Favour strong incumbents and invites spiteful bidding

[1] SMRA: Simultaneous Multi-round Rising Auction.
[2] CCA: Combinatorial Clock Auction.
[3] Lowest price needed to justify allocation given rival bids, and avoid ‘unhappy losers’ (i.e. no rival willing to pay more for lots secured by the winner).

Spectrum award mechanisms (2)

In the recent 3.5 GHz award in France, ARCEP allocated 50 MHz on an administered basis to each operator, while auctioning the remainder.

ARCEP's hybrid administered plus auction approach provides the best of all worlds: risk reduction without necessarily interfering too deeply with the final allocation.

A hybrid administered / market-based approach offers a potentially efficient third way

Example: allocation of 400 MHz at 3.5 GHz in a market with 3 broadly equivalent operators

- 400 MHz not obviously divisible by 3
- Hybrid approach: allocate 100 MHz each to all players and auction the remaining 100 MHz[1]
- Each operator gets a viable starting point which they do not need to fight over
- Guarantees a minimum level of efficiency, since an outcome in which one operator secured less than 100 MHz would likely be undesirable
- Also reduces the potential adverse impact of strategic bidding, because this problem would be confined to residual spectrum rather than the entire 400 MHz on offer

Example: 3.5GHz award in France (2020) – striking a reasonable balance

- 310 MHz available[2], 4 MNOs
- 50 MHz allocated administratively to each – giving each a reasonable starting point in this key 5G band
- Remaining 110 MHz auctioned – giving a chance for up to 2 operators to secure 100 MHz each in the band, if this were indeed efficient

	Orange	SFR	Bouygues	Free
Administered allocation	50 MHz	50 MHz	50 MHz	50 MHz
Auction: allocation of 110 MHz	40 MHz	30 MHz	20 MHz	20 MHz
Holdings at the end of the award	**90 MHz**	**80 MHz**	**70 MHz**	**70 MHz**

The outcome broadly reflects the relative position of operators within the market

Importantly, this hybrid approach minimised the risk of collective overpayment: only the marginal 110 MHz were contested, helping contain total prices paid by operators for their 3.5 GHz holdings

[1] Process could also accommodate market entrants, if there are any –e.g. they could bid for or be awarded the residual 100 MHz.
[2] A further 90 MHz in the 3.5GHz band will be allocated in 2026, when the licences of legacy users expire.

Trade-off between licence fees and socio-economic outcomes (1)

The State cannot extract vast amounts of capital from critical industries without diminishing the productivity and welfare benefits that these industries generate for society.

The 'sunk cost' hypothesis is amply refuted both by experimental and empirical evidence.

It is sometimes argued that lump-sum fees charged for operator-licences do not bear on subsequent management decisions, because these fees effectively become sunk costs

- According to the theory, operators seek only to maximise future returns, and past costs do not alter optimal, forward-looking strategies
- If this 'sunk cost' hypothesis were true, then short of bankrupting the industry, regulators could charge as much as they wished to renew licences, with little or no effect on retail market outcomes
  - This would represent a 'free lunch', in which the state could extract maximum licence payments from the industry while maintaining all of the welfare benefits generated by the industry's activities
  - Yet this hypothesis is amply refuted by both experimental and empirical evidence

Experimental evidence (Offerman and Potters, 2006)

- Study involving 166 students in Economics and Management from Tilburg University in the Netherlands, split into 3 groups
- Examined whether subjects' pricing decisions in competitive games was influenced by prior auction or fixed licence payments

Group1
Large upfront licence fee

Group 2
Auction leading to upfront licence fee

Group 3
No upfront licence fee

Compare pricing decisions in competitive games

Outcome:

*"**Both in the fixed cost and the auction treatment players charged significantly higher prices than in the baseline treatment**. In the long term, when the entry licences had been re-allocated a couple of times, the difference in average price levels between the treatments tended to become smaller. Nevertheless, even in the longer term, we found a significant positive correlation between entry fees and prices"*

Evidence of reaction by rational agents: large upfront fees are likely to lead to higher prices and/or reduced investment

Trade-off between licence fees and socio-economic outcomes (2)

In Finland, the annualised cost of spectrum amounts to a mere 1.4% of mobile industry revenue.

As a result, mobile operators in Finland have built a very high-density mobile network which delivers excellent availability and high download speeds.

There is extensive direct (historical) evidence that high spectrum fees lead to inferior market outcomes

Netherlands and Austria multiband awards (2012, 2013)

- CCA format used in both countries
- Total spectrum cost between 25% and 33% of total Enterprise Value
- Netherlands: allocation entirely consistent with relative market positions, yet high price paid
  - Spiteful bidding[1] can result in collective overpayment

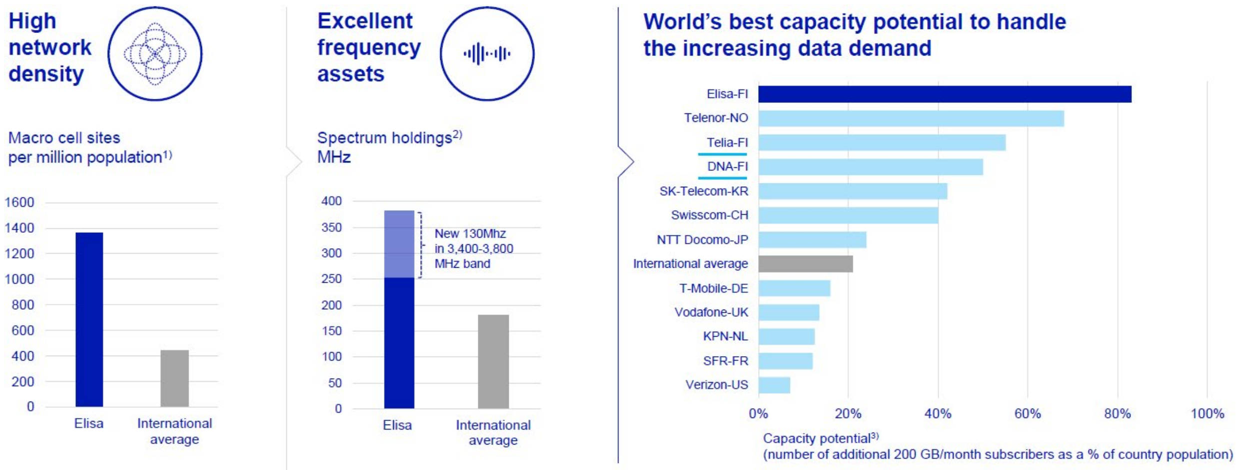
European Commission reaction[2]:

*"Was nothing learned from previous auctions for UMTS [3G] frequencies, when the share price of KPN dropped substantially and the ecosystem of small supply companies in the telecom sector was severely damaged? … **Telecom companies paid high prices. KPN saw a further decline in its credit rating. Prices for attracting money for infrastructure investments are expected to rise. The rollout of high-speed internet will slow down** and the suppliers will be put out of business. This 'Christmas gift' could be a huge burden for the sector, and for all other businesses, entrepreneurs and citizens who need super-fast mobile internet"*

Finland

- Finland has consistently pursued a policy of low spectrum fees in to allow operators to invest more in their networks
- Annualised cost of spectrum amounts to a mere 1.4% of mobile industry revenue

Outcome: 3 of the top 4 best performing MBB networks are in Finland (2018)



[1] *Spiteful bidding in a CCA: overstate bids for larger packages to drive prices paid by rivals – to avoid embarrassing price differentials.*
[2] *Neelie Kroes, Vice President European Commission and Digital Agenda Commissioner, in January 2013.*

Trade-off between licence fees and socio-economic outcomes (3)

As a % of revenues, the annualised cost of spectrum in Germany is almost 10x higher than in Finland – and prices (for 5G Unlimited) are almost 3x higher.

There is extensive direct evidence that high spectrum fees lead to inferior market outcomes

Finland: annualised cost of spectrum **~1%** of operator revenue

Germany: annualised cost of spectrum **~10%** of operator revenue

Unlimited 5G costs <u>2.7x more</u> in Germany than in Finland – while 6GB in Germany costs more than unlimited in Finland

- Assuming a 5G speed of 20 Mbit/s for 4K YouTube streaming, 6GB equates to just 1.33 minutes of 5G per day
- From a consumer's perspective, what is the point of 5G with a 6GB allowance?

<u>European Commission view:</u> "Reliance on auctions should not lead to an excessive transfer to the public budget or for other purposes to the detriment of low tariffs for the users"

Trade-off between licence fees and socio-economic outcomes (4)

As of 2009, the ratio of social gains was around 240-to-1 in favour of mobile services over licence revenues in the US.

Based on 2017 cross-country research, increases in welfare exceed foregone mobile licence fee receipts by an average of 2.5-to-1.

Research in the US based on data from 1991-2008 shows that welfare gains from mobile dwarf social gains from auction fees

Results obtained by Hazlett, Munoz et al (2012)

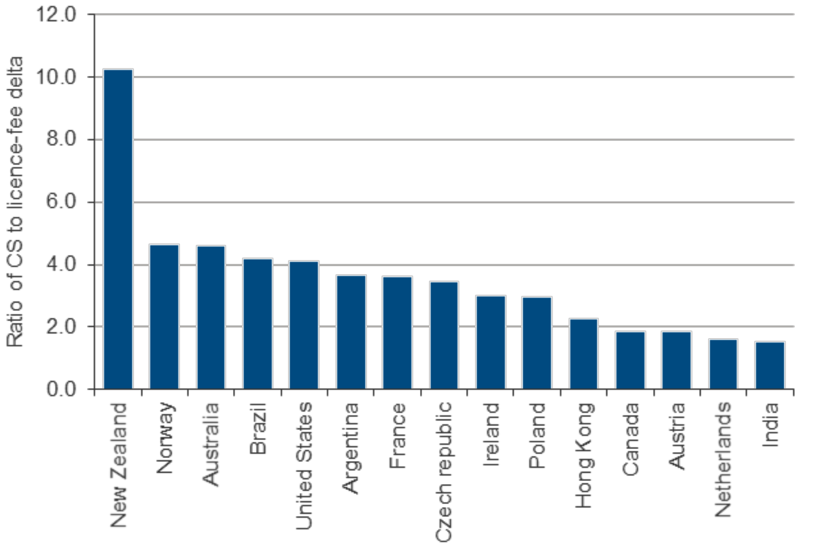
- 2009 CS[1]: $4000 bn present value
- 80x total auction revenue up to 2008
- With 33% deadweight losses, the net social gains from the $50bn in auction revenues is just $17bn (0.4% of the CS)

- On this basis, the ratio of social gains was 240-to-1 in favour of mobile services over licence revenues
- This puts spectrum pricing policy into sharp focus; according to the authors:

> *"…to maximise consumer welfare, [telecoms policy] should avoid being distracted by side issues like government licence revenues."*
>
> *"A policy that has an enormous impact in increasing license revenues need impose only tiny proportional costs in output markets to undermine its social utility. So, for example, **a new auction design that (heroically) doubled auction revenues would, if it reduced consumer surplus by just one-half of one percent, produce costs in excess of benefits**".*

Quantitative research by NERA shows that welfare gains exceed reductions in licence fees by 2.5x on average

Ratio of increases in welfare to reductions in licence fees



- Based on a sample of 15 countries
- NERA analysis shows that reductions in licence fees would be more than offset by increases in CS; according to the authors:

> *"…where governments adopt policies that extract excessive financial value from the mobile sector in the form of high fees for spectrum, a significant share of this burden is passed onto customers through higher prices for mobile and lower quality data services."*

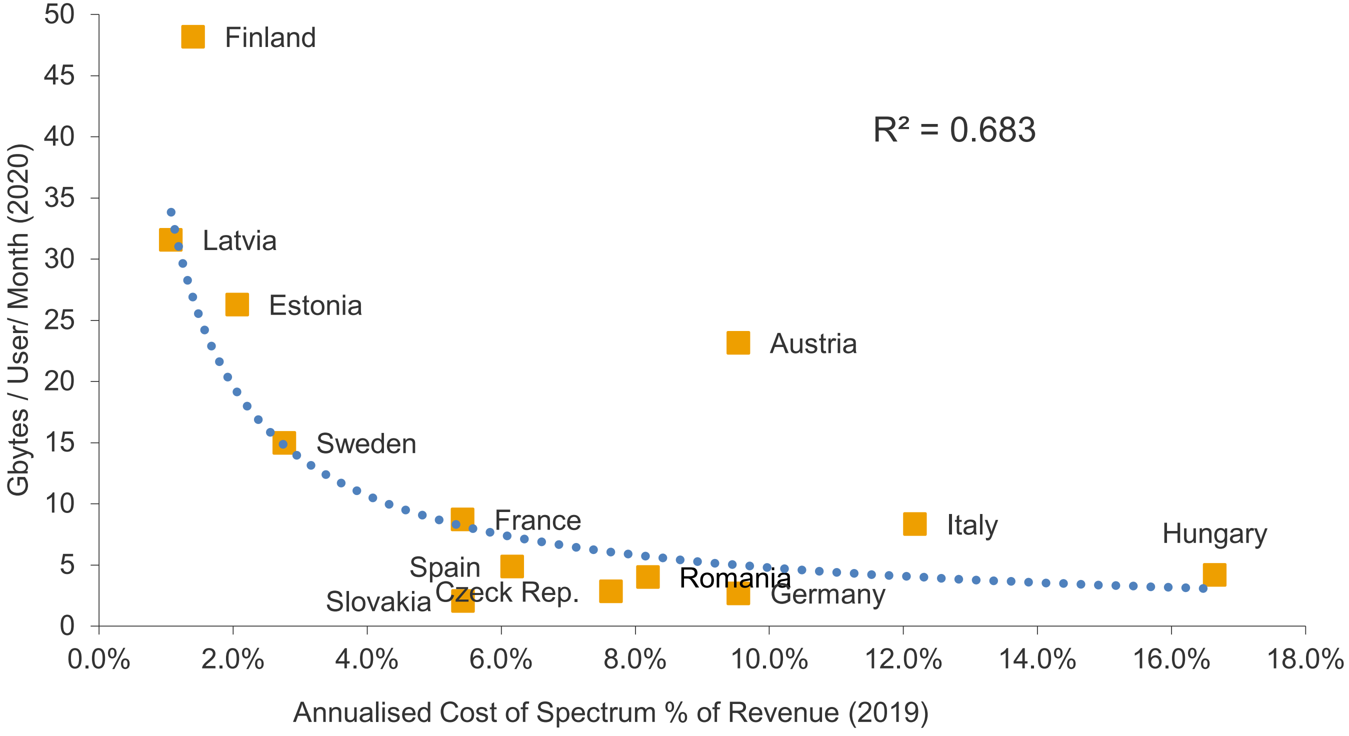
[1] *CS: Consumer Surplus (welfare).*

Trade-off between licence fees and socio-economic outcomes (5)

68% of the variation in mobile consumption intensity between countries is explained by differences in the annualised cost of spectrum.

A study of the cost of spectrum in 13 EU countries for the European Commission shows that the lower cost of spectrum the higher the consumer value

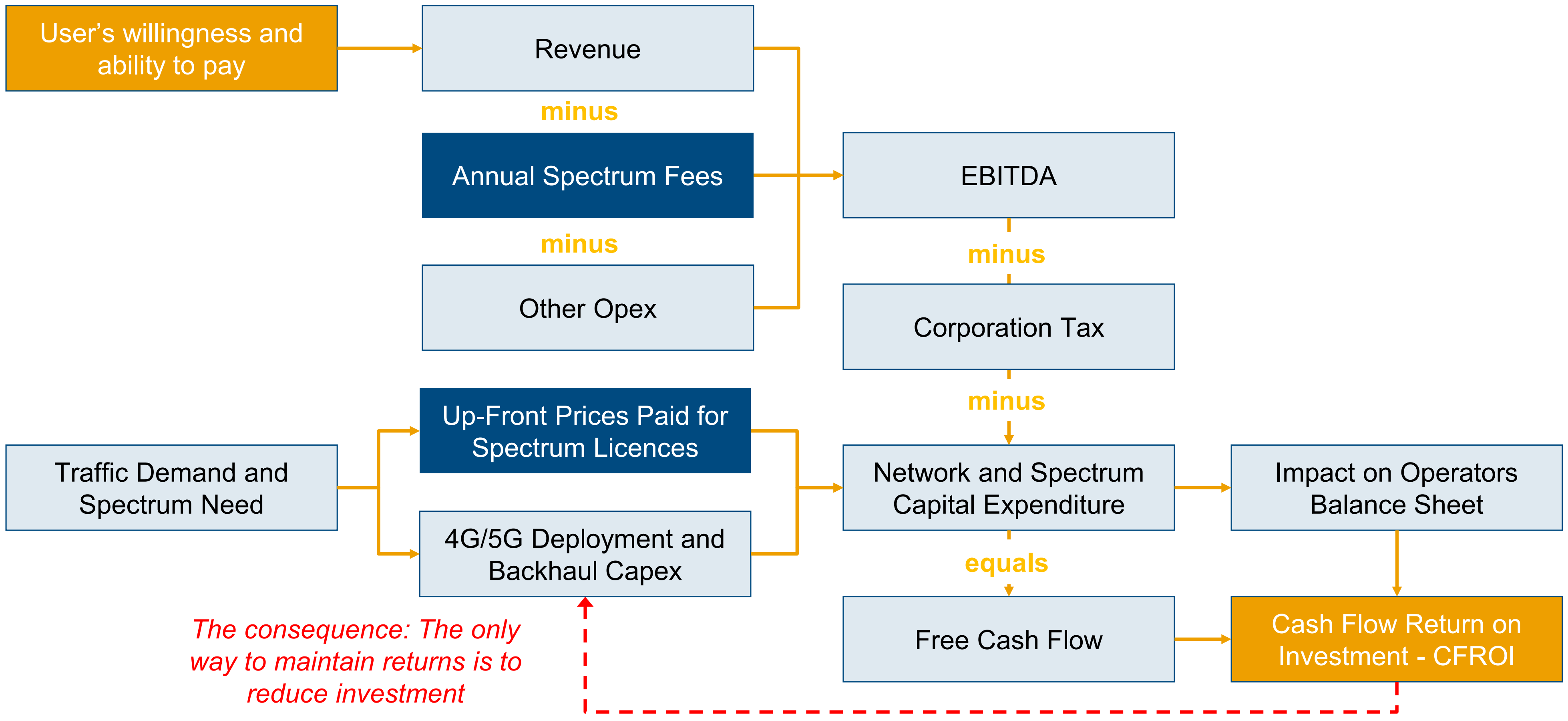
- This study shows a strong inverse relationship between spectrum costs and consumption levels, underscoring the trade-off between spectrum fees and consumer welfare
- It also highlights the likely negative impact of high spectrum fees on economic development, on the premise that lower utilisation of mobile communications' services leads to foregone gains in productivity



Sustainable spectrum pricing (1)

Spectrum pricing is only sustainable if operators have a reasonable prospect of earning their cost of capital (WACC) while competing both on quality and on price.

Leaving aside the direct and indirect economic evidence, as illustrated in the previous slides, it should seem obvious that high costs of spectrum will diminish the ability of operators to invest and to compete more aggressively on price



Sustainable spectrum pricing (2)

Revenues per MHz are falling, so prices per MHz need to fall too in order to remain sustainable.

Clearly the more capital is transferred from the industry to the state for spectrum usage rights, the less remains available to invest in actual networks.

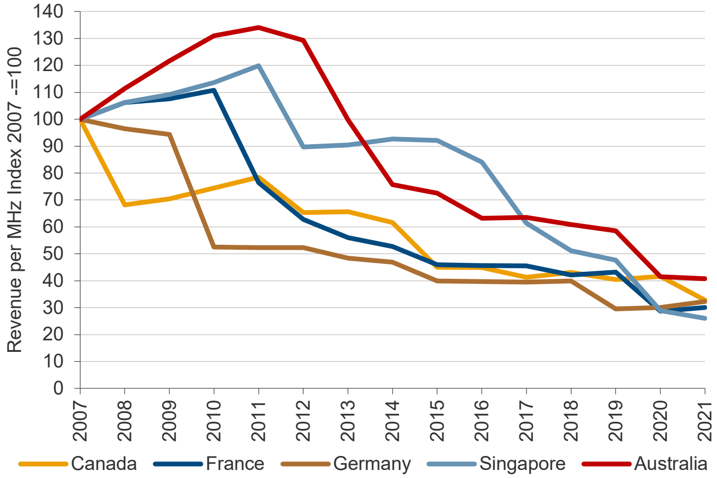
There seems to be an expectation among policymakers that the value per MHz of incremental spectrum should remain the same or increase

- However, if revenues do not increase, it follows that revenues per MHz decline as holdings increase
  - This is indeed what has been observed in most markets, where revenues have stagnated or declined during the last 10 years (see earlier slides)
- If, in addition, *average* spectrum TCO per MHz remains constant, then it follows that the financial burden on the mobile industry increases every time new spectrum is released

Broadly flat industry revenues coupled with increasing total spectrum costs quickly become unsustainable

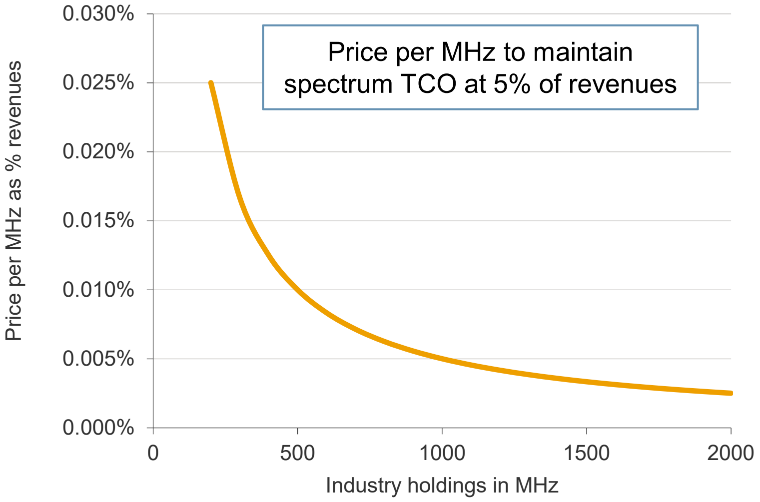
- For example, total costs of spectrum ownership (TCO) above **10%** of industry revenues would represent around **60%** of typical mobile operator budgets – a very significant capital outlay before spectrum is deployed on even a single site[1]

Revenues per MHz have fallen over time



The trend of falling revenues per MHz is set to persist to 2030, with further spectrum awards (since 2021), and flat or falling revenues in real terms (see Ch.1)

Spectrum TCO per MHz must fall too, to remain sustainable



[1] Based on GSMA forecast implying that capex will average 17% of service revenues between 2020 and 2025.

Sustainable spectrum pricing (3)

Regulators can assess the sustainability of spectrum pricing in their market by looking at the annualised cost of spectrum as a percentage of mobile operator revenue.

As a rule of thumb, spectrum prices may become unsustainable when TCO exceeds 10% of revenues.

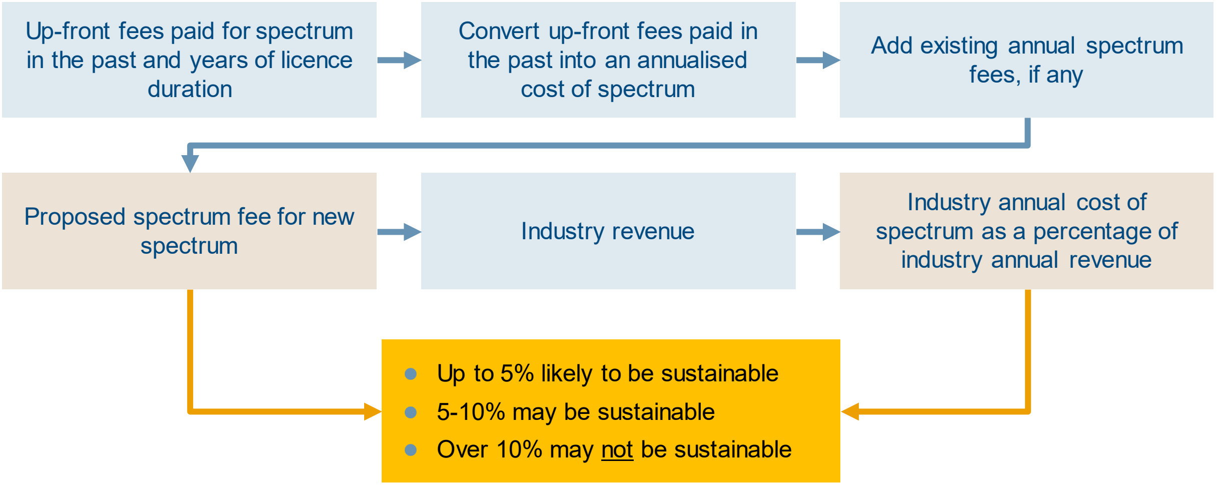
Provided that the market is competitive, higher spectrum prices are invariably worse for all stakeholders than lower prices[1]

The 'spectrum price index' (SPI) is a metric favoured by some regulators (e.g. ICASA in South Africa and Anatel in Brazil) to gauge the sustainability of spectrum pricing[2]:

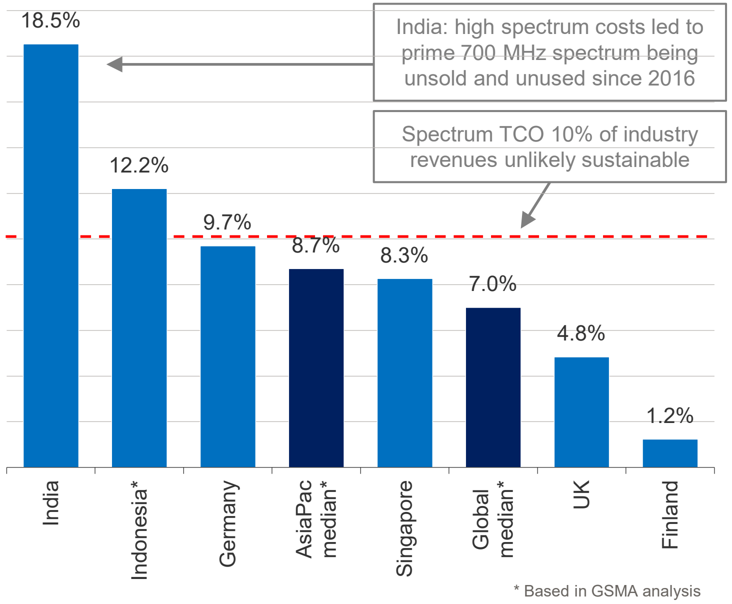
$$\textbf{Spectrum Price Index (SPI)} = \frac{\textbf{Spectrum Licence TCO}}{\textbf{annual ARPU} \times \textbf{Subscribers}}$$

- Total costs of spectrum ownership (TCO) takes account of the ongoing economic cost of lump-sum payments plus any annual licence fees paid by operators
- The economic cost of upfront lump-sum payments takes the time-value of money into account[3]

Gauging the sustainability of fees for new spectrum:



Sample SPI values: spectrum TCO as % revenues



Abundant spectrum priced reasonably best serves public interests:

- Promotes investment in coverage and capacity
- Enables deeper price erosion through competition
  - While allowing industry to earn its cost of capital
  - Thus, promoting sustainability of competition
- As a rule of thumb, if the aggregate spectrum TCO of all spectrum holdings exceed 10% of combined revenues, substantial damage to public interests may ensue

[1] Based on analysis shown in previous slides. [2] Source: discussions with Huawei [3] The calculation is based on the equivalent annual licence fees that would be equivalent in economic terms to the actual upfront lump-sum paid. This 'annual equivalent cost' (AEC) is calculated as follows (where Lump= upfront fee, WACC = industry cost of capital, duration is the licence term in years): AEC = Lump x WACC / (1 – (1/(1+WACC))^duration))

Sustainable spectrum pricing (4)

In addition to negative socio-economic consequences, excessive spectrum pricing may lead to unsold spectrum (hence foregone income for the state).

Unrealistic spectrum pricing is already impacting negatively on spectrum use and damaging competitive 4-5G service provision

In many countries mobile spectrum auctions have been a substantial source of Government revenue.

The difficult, but necessary message to politicians is that they need to find alternative sources of revenue.

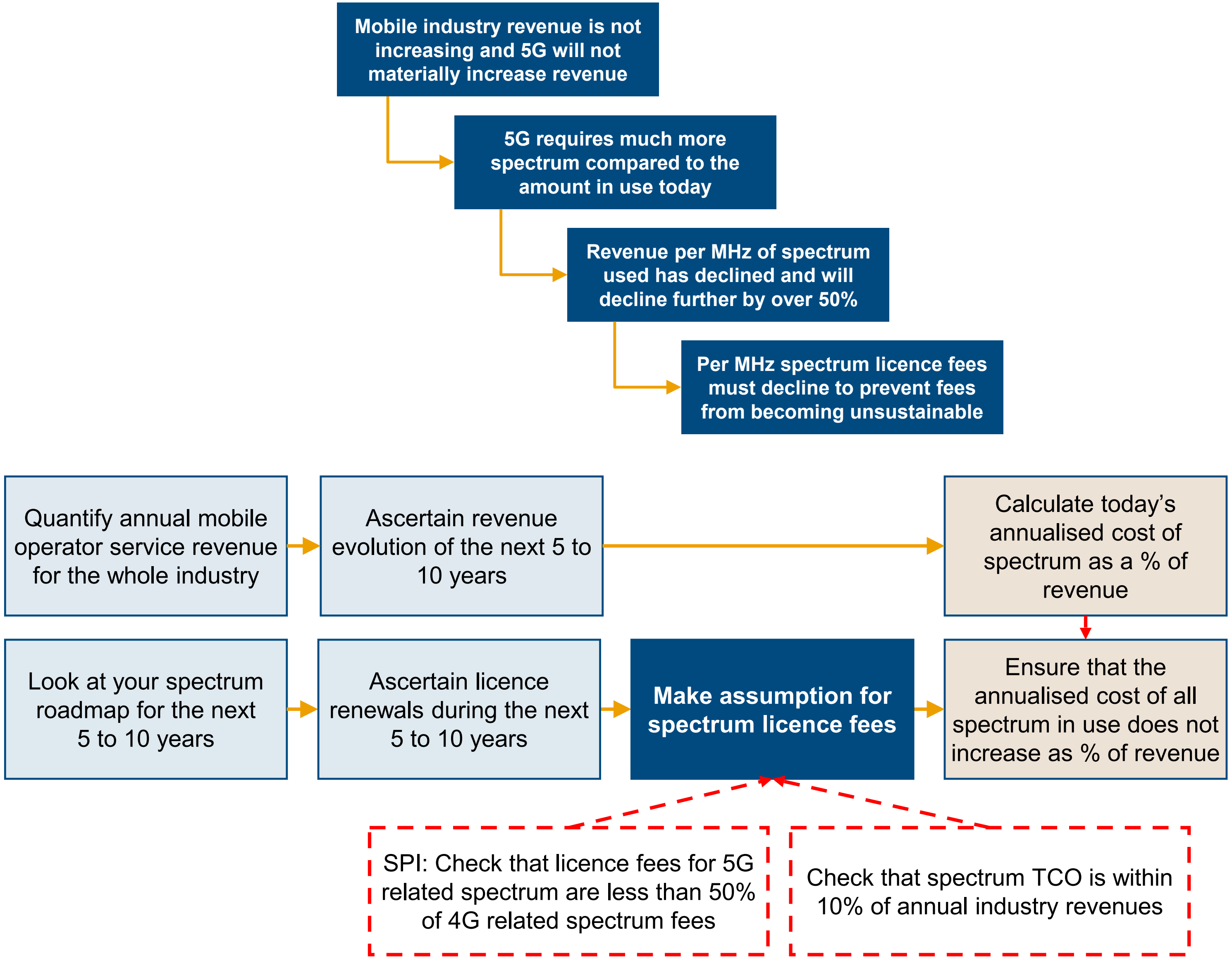
Governments have missed spectrum revenue targets in Australia, Pakistan, India, Bangladesh, Mexico, Ghana, Mozambique, Senegal.

Relevant examples include:

- **Bangladesh** was the last country of in the world to launch 4G because the regulator prevented refarming to raise revenue from selling new spectrum – leading to delay in the launch of 4G/5G
- As a response to the economic crisis and pressure from external bodies to increase tax revenues in **Sri Lanka**, the TRC increased the spectrum price factor by **20%** in 2023
  - A crisis in the sector followed, with all operators posting tax losses in 2023
  - This arbitrary increase in spectrum prices pushed the spectrum TCO to over **20%** of revenues for the 2 smaller players in the market – their long-term viability now in doubt
- Operators with a low market share cannot survive when spectrum fees are excessive – examples include: **Nepal**, **Bangladesh**, **Sri Lanka**, **Ghana**, **Mexico**, **Brazil**
- Excessive prices lead to spectrum remaining unsold at auction and lying fallow for many years – examples include: **India**, **Pakistan**, **Bangladesh**

Sustainable spectrum pricing (5)

Regulators should consider the industry position as well as the entire spectrum roadmap when setting spectrum prices.



Spectrum licence duration, renewals and trading

Long-term regulatory certainty reduces risk for operators and incentivises investment.

Policies that yield greater certainty while promoting efficient spectrum use generally reflect best international practice.

Issuing mobile spectrum licences with long or indefinite durations give certainty to operators and incentivise investment

- EU policy: spectrum licences of "at least 20 years to promote investment, in particular in 5G connectivity"[1]
- Spain: government taking steps to extend mobile spectrum licence durations to 40 years[2]
- US, UK: indefinite licences (UK: with annual licence fees paid after initial term)
- Note: indefinite licences require appropriate rules to retain long-term flexibility in spectrum management (e.g. provisions to revoke licences with due notice and/or compensation if compelling spectrum management reasons exist)

Strong expectations of licence renewal upon expiry gives certainty to mobile operators and incentivises investment

- Providing spectrum is reasonably widely deployed by mobile operators, it is generally the case that they will be the most efficient users of those resources
  - Existing users would tend to value their own spectrum-in-use more highly, as deployment costs would already have been incurred, while alternative users would still have to bear these (hence these incremental costs would be netted off from the latter's spectrum valuations)
  - However, there are exceptions: distressed mobile operators may fail to deploy spectrum widely, leading to inefficient use; non mobile operators (such as FWA-only operators) tend to operate on a more localised basis, leading to far less efficient use of spectrum than nationwide mobile operators
- Barring such exceptions, it is generally best international practice to adopt (semi-)automatic spectrum licence renewal processes
- Accordingly, auctions for expiring mobile spectrum should be avoided
  - They are prone to drive higher costs for operators, with potentially significant transfers of essential capital from the industry to the state
  - They may also yield less efficient outcomes as a result of spiteful bidding between rival operators

Spectrum trading generally promotes efficient use

- While voluntary mobile spectrum trades are relatively uncommon (possibly due to aversion to selling prime assets to direct competitors), trading provisions do offer an opportunity for less 'efficient' users of a resource to sell to parties that value the resources more highly, and who would thus be likely to use them more efficiently
- The sale of 2.6GHz TDD spectrum in the UK by BT to rival Telefonica UK is a case in point

[1] *Directive (EU) 2018/1972* . [2] *Source: rcrwireless.com, May 2023*

Other licence conditions and policies

Regulators may set coverage obligations, but it would be absurd for them to dictate how operators achieve this.

Similarly, licences should be technology-neutral: technology choices should be for the operators to determine, without undue regulatory constraints.

Coverage and/or Quality-of-Service (QoS) obligations are far better than high spectrum fees

- Coverage obligations or commitments (e.g. in exchange for lower spectrum fees) is a far better policy than the pursuit of direct spectrum revenues for the state
- Coverage obligations may include minimum (outdoor) data-speed targets (as were applied by Ofcom in relation to an 800 MHz ‘coverage lot’ during the 2013 Digital Dividend auction)
- However, it is important that any coverage obligation be technology and spectrum-neutral: mandating deployment in a specific band, for example, could led to inefficient deployment, as different bands may be more fit for purpose in distinct areas – this is best left to the operators

Technology and service neutrality is essential to promote efficient spectrum use

- Technology neutral licences are now the norm in advanced economies
- Competition incentivises operators to pursue efficient technology strategies – it would be absurd for regulators to dictate or constrain the technology strategies of operators
- A lack of technology neutrality may also dissuade investment and innovation, which would be socially harmful

Wideband allocations are more efficient from both a cost and channel-performance perspective (see Ch.2)

- Regulators should favour larger, contiguous holdings across fewer bands (wide band allocation)
- Regulators should also seek to avoid split assignments within any given band – these are inefficient from both a performance and cost perspective, and future defragmentation may lead to equipment write-offs

Phased spectrum licence payments are easier for operators to finance

- Phasing of licence payments is generally a good policy, as these can be financed more readily through cash flows rather than capital raises
- However, phased licence payments may be inappropriate in situations where private parties seek speculative gains from spectrum trading[1]

Timing of licence awards

- Regulators should seek to accelerate the clearing of mobile-designated spectrum from legacy users and release the usage-rights to operators as quickly as possible (as soon as it is available) – however, auctioning spectrum while it is still to be cleared may be counterproductive
- Delays in spectrum awards constrain supply and consumption, leading to foregone social gains

[1] This situation may arise when prospective entrants are invited to bid for spectrum licences. The risk is that such parties acquire spectrum with a view to selling it at a higher price to incumbent operators, and phased payments could allow them to attempt this with little risk (without due safeguards, they could simply hand back the spectrum without significant further payment of fees if their strategy fails).

10

Policies to accelerate network expansion

Further public policies levers to promote network expansion and to support rural broadband

Streamlining local planning processes

All too often, local planning processes and constraints are a major barrier towards network expansion.

Easing the planning bottleneck should be a major policy priority.

In many countries, the overall site acquisition process is too slow and too costly

Typical site acquisition and deployment process[1]:

The local planning process is the one area that is outside the control of operators – failed applications lead to deployment delays and add significant costs

- Streamlining these processes is key to accelerate the deployment of (5G) macros sites and small cells (to secure the benefits of mobile for local businesses and consumers)
- Initiatives in different markets to ease planning bottlenecks; examples include:

United States: FCC '5G Fast Plan' (2018) aimed at securing global 5G leadership

- Reducing State/municipal response periods to 60 days to review a proposed collocation and 90 days to for new structures
- 'One-touch-make-ready' to speed up the deployment of network equipment and backhaul on utility poles, and restrictions on the fees charged by municipalities
- Exclusion of small cells from the Environmental Policy Act and the Preservation Act
- Restrictions on the fees charged by municipalities for access to assets

The EU recognises need to reduce the cost of building 'local 5G connectivity (Small Cells)'[2]

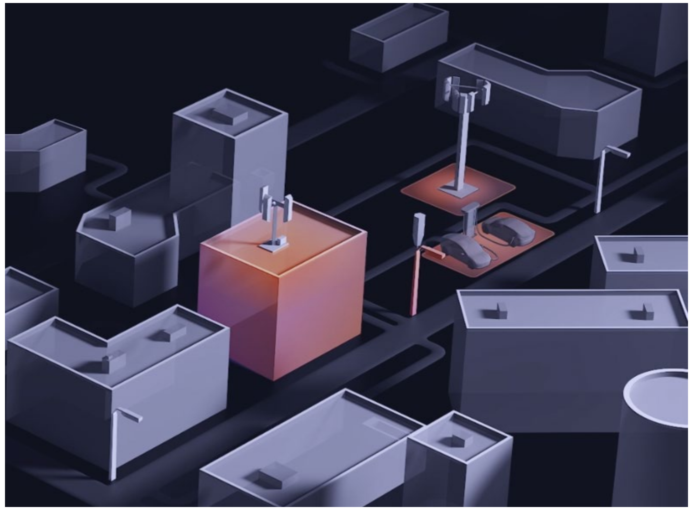
- Policies pursued to facilitate the deployment of small cells include:
  - Not to hinder the deployment of small cells meeting specified characteristics (with exceptions of areas of architectural, historical or natural value)
  - Rules governing the deployment of small cells to be nationally consistent
- In the Netherlands, mobile telecom antennae of less than 5 meters in height are already exempted from any environment authorisation (subject to conditions, set by Decree)
- In the context of 4G/LTE initial measures adopted by some Member States include the use of generic permits, harmonised planning permissions, 'one stop shop' application procedures, tacit approvals and databases of qualified candidate site locations

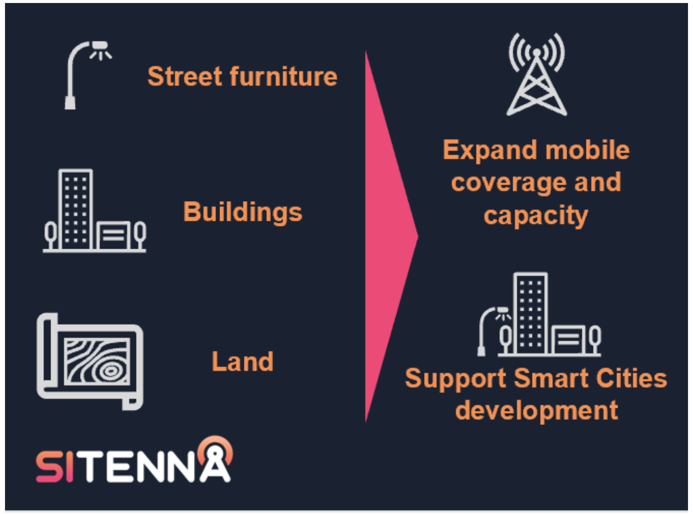
[1] *Source: Sitenna (Satara Technologies).*
[2] *Source: EC COCOM 5G Working Group document (Oct 2018).*

Providing access to public assets for mobile deployment

Providing access to public assets for mobile deployment drives socio-economic benefits, future-proofs communities and generates incremental income for (local) government.

Municipalities and other public bodies can leverage their assets to promote local inward investment in critical infrastructure





Images courtesy of Sitenna.com

Case study: UK

- UK policy regulates rental fees that landlords can charge operators for mobile site leases
  - Setting rental income on a ‘cost basis’ effectively removed a key incentive for landlords to make real-estate assets available to operators
  - The unintended effect of the policy has been to constrain supply, limiting site options for operators across the nation
- To overcome the shortfall, the UK government has sought to stimulate supply from the public sector (such as local councils and ‘highways’ authorities) – however, a number of obstacles needed addressing:
  - Planning processes and rules are set locally, and public asset data and management capabilities varied significantly across different councils
  - With reduced incentives from direct rental income, the business case for municipalities centred around improving connectivity for local businesses and residents – driving socio-economic gains from greater digital participation
- The government launched a ‘Digital Connectivity Infrastructure Acceleration (DCIA)’ Programme[1], to improve local asset data and capabilities, and to educate councils on the socio-economic benefits of increased mobile network deployment
- A DCIA pilot programme (2021) brought mobile operators, neutral hosts/towercos, asset-management platform providers and 8 local government consortia together to:
  - Develop and test standardized, streamlined processes, improve asset databases and enable operators to quickly identify site options through online platforms
  - With a view to expanding adoption via an Early Adopter’s Group and beyond

Notwithstanding challenges in the fragmented UK public real estate market, the UK government recognised the importance of policies facilitating mobile network deployment and aimed at reducing overall network costs for the industry

[1] See: https://www.gov.uk/guidance/digital-connectivity-infrastructure-accelerator-programme.

Supporting rural broadband

Rural broadband is often unprofitable. Without government support, rural broadband will continue to lag, perpetuating the digital divide.

Subsidies for rural broadband development can help overcome economic barriers and promote digital inclusion

- Whether fixed or mobile, adequate rural broadband is costly to provide and often unprofitable
- Government support is needed to help bridge the digital divide
- A mix of fixed, fixed wireless (including mmWave) and satellite is plausibly needed to best address rural connectivity needs – with different access mechanisms being most suitable in distinct rural settings

Internet providers have left rural Americans behind

Headline and image from *The Guardian*, 17 March 2024

Case study: US government funding for rural broadband

- Multiple programmes, administered respectively by the FCC, NTIA and the US Department for Agriculture, totalling $97 billion[1]
- Targeted at areas where data speeds are below 100 Mbps downlink and 20 Mbps uplink (the threshold targeted for all US homes by 2027)
- Procurement typically via reverse-auction – attracting bids from a range of providers spanning fixed, FWA and satellite (e.g. Starlink)
  - Albeit the FCC later rejected Starlink from $900 million in subsidies in a smaller rural internet program, saying the company had failed to prove it could meet the requirement of a 100 Mbps download speed and 20 Mbps upload speed[2]

The sheer scale of US government support underscores the social value it places in overcoming the digital divide

[1] *Source: Nokia.*
[2] *Source: Washington Post, 1 May 2024..*

11

Concluding remarks

Summary: international best practices and calls to action

International best practices – overview

Best practices imply evidence-based policies designed to improve mobile market outcomes for consumers and society.

With so much at stake, it is important to pursue policies that promote investment, innovation and competition.

Regulatory certainty	• Investors need long-term certainty – a stable policy landscape incentivises network investment • Perpetual or longer duration spectrum licences foster investment (European Commission view: at least 20 years; FCC: perpetual licences; Ofcom UK: perpetual licences with annual fees after initial term)
Moderate licence fees	• Avoid harm to investment and retail prices by driving up costs of key industry inputs • Coverage commitments in exchange for lower spectrum fees is better than fee maximisation • Phasing of licence payments is generally good policy, avoiding the need for operators to raise extra capital
Technology neutrality	• Technology neutral licences are now the norm in advanced economies • Competition incentivises operators to pursue efficient technology strategies • Lack of technology neutrality may also dissuade investment and innovation
Spectrum packaging	• Regulators should favour larger, contiguous holdings across fewer bands (wide band allocation) • Regulators should avoid split assignments within any given band – these are inefficient from both a performance and cost perspective, and future defragmentation may lead to equipment write-offs
Timing of awards	• Regulators should seek to accelerate the clearing of mobile-designated spectrum from legacy users and release the usage-rights to operators as quickly as possible (i.e. as soon as it is available, but not before) • Delays in spectrum awards constrain supply and consumption, leading to foregone social gains
Spectrum trading	• Regulators should promote spectrum trading (subject to competition safeguards) • While an operator may be the most efficient spectrum user at a given time, a rival might make better use of resources (and value these more highly) at a later point – trading could thus improve overall efficiency
Leverage public assets & support rural broadband	• Streamlining planning processes and making public real-estate assets (buildings and street furniture) readily available for mobile network deployment will serve the interests of local businesses and consumers • Subsidies for rural broadband development help overcome economic barriers and promote digital inclusion

Calls to action

The fast-changing mobile landscape brings both risks and opportunities.

Operators and policymakers need to respond positively to these challenges to ensure favourable outcomes.

Operators and regulators need to work together to create the foundations for a sustainable future for the industry

Call to action: Regulators

While mobile operators are often major contributors to the exchequer, capital extraction from the industry may have disproportionate indirect consequences for welfare and economic development.

We would therefore urge regulators to tread carefully, and to hold these aspects closely in mind when setting policy.

We would also call on regulators to support this critical industry by:

- Release as much spectrum as possible, as fast as possible, and at sustainable prices
- Facilitate wide band deployments on a technology neutral basis, through spectrum allocation policy as well as by fostering spectrum trading and sharing
- Pursue technology-neutral spectrum policies
- Provide regulatory certainty through stable, evidence-based policy development directed at maintaining a sustainable mobile telecoms landscape
- Pursue policies that reduce the financial burden on the industry, to foster future sustainability, promote investment and innovation, while and maximising room for further retail price erosion

Call to action: Operators

Harnessing the full potential of new and emerging technologies, and making the best use of available spectrum should remain central to the plans of operators

- Embrace the opportunities of 5G Advanced – to drive efficiencies, unlock incremental revenue opportunities, and prepare for 6G
- Address capacity and coverage shortfalls to secure competitive advantage and maximise potential revenue, while serving the needs of society
- Compete intelligently:
  - Share passive networks to minimise their drag on collective returns
  - Partner with complementary infrastructure providers (e.g. satellite, WiFi) to foster hyperconnectivity
  - Partner with complementary solutions providers to address wider opportunities in enterprise and industry, within the wider IoT value-chain and across mobile digital applications
- Pursue spectrum consolidation, whether through spectrum trading or through spectrum sharing – to enable more efficient and cost-effective wide band deployments
- Introduce pricing innovations such as priority-based data packages to better align value with willingness to pay, improve outcomes across the customer base, and avoid commoditisation

Appendix A

TDI calculations

TDI calculations – Actual traffic (constrained demand)

MBB demand	2023	2030	Multiple	Calculation	Comments
Total MBB SIM penetration	86.5%	96.7%	1.1x	A1	Based on third-party forecasts
4G penetration (SIMs per capita)`	67.8%	30.3%	0.4x	B1 = A1 - E1	
4G usage per SIM (GB/month)	17.7	29.7	1.7x	C1	Based on third-party forecasts
4G usage per capita (GB/month)	12.0	9.0	0.7x	D1 = B1×C1	
5G penetration (SIMs per capita)`	18.7%	66.4%	3.6x	E1	Based on third-party forecasts
5G usage per SIM (GB/month)	21.9	67.7	3.1x	F1	Based on third-party forecasts
5G usage per capita (GB/month)	4.1	45.0	11.0x	G1 = E1×F1	
Total MBB usage per capita (GB/month)	16.1	54.0	3.3x	H1 = D1 + G1	
Population growth factor (2023=100%)	100%	105%	1.1x	P	Based on third-party forecasts
Total MBB usage per 2023 capita (GB/month)	16.1	56.8	3.5x	T1 = H1×P	
MBB index	**79.9**	**281.5**	**3.5x**	I1 = T1×Nc	Indicates traffic trend

FWA demand	2023	2030	Multiple	Calculation	Comments
Total FWA SIM penetration	1.6%	4.3%	2.6x	A2	Based on third-party forecasts
4G penetration (SIMs per capita)`	1.2%	0.5%	0.4x	B2 = A2 - E2	
4G usage per SIM (GB/month)	216.7	252.8	1.2x	C2	Based on third-party forecasts
4G usage per capita (GB/month)	2.6	1.4	0.5x	D2 = B2×C2	
5G penetration (SIMs per capita)`	0.4%	3.7%	8.5x	E2	Based on third-party forecasts
5G usage per SIM (GB/month)	267.3	576.1	2.2x	F2	Based on third-party forecasts
5G usage per capita (GB/month)	1.2	21.4	18.3x	G2 = E2×F2	
Total FWA usage per capita (GB/month)	3.8	22.8	6.0x	H2 = D2 + G2	
Population growth factor (2023=100%)	100%	105%	1.1x	P	Based on third-party forecasts
Total FWA usage per 2023 capita (GB/month)	3.8	23.9	6.4x	T2 = H2×P	
FWA index	**18.7**	**118.7**	**6.4x**	I2 = T2×Nc	Indicates traffic trend

IoT demand	2023	2030	Multiple	Calculation	Comments
Total IoT devices per capita	0.34	0.63	1.8x	A3	Based on third-party forecasts
GB/month per device	0.8	4.2	5.0x	B3	Based on third-party forecasts
IoT traffic per capita (GB/month)	0.3	2.6	9.1x	D3 = A3×B3	
Population growth factor (2023=100%)	100%	105%	1.1x	P	Based on third-party forecasts
Total IoT traffic per 2023 capita (GB/month)	0.3	2.8	9.6x	T3 = D3×P	
IoT index	**1.4**	**13.8**	**9.6x**	I3 = T3×Nc	Indicates traffic trend

Total mobile data demand	2023	2030	Multiple	Calculation	Comments
Total traffic per 2023 capita (GB/month)	20.2	83.5	4.1x	Tc = T1 + T2 + T3	
Normalisation factor	5.0	5.0		Nc = 100/Tc(2023)	
TDI (constrained)	**100.0**	**413.9**	**4.1x**	TDIc	Indicates total traffic trend

TDI calculations – Impact of network suppression

Coverage	2023	2030	Multiple	Calculation	Comments
4G population coverage	90.0%	95.0%	1.06x	PC1	Based on third-party forecasts
5G population coverage	49.0%	87.4%	1.78x	PC2	Based on third-party forecasts
Penetration if coverage were 100%	**2023**	**2030**	**Multiple**	**Calculation**	**Comments**
Unconstrained MBB penetration	96.1%	101.8%	1.1x	A1u = A1 / PC1	4G coverage taken as total network coverage
Unconstrained 4G MBB penetration	58.0%	25.8%	0.4x	B1u = A1u - E1u	We assumes linear relation between coverage and adoption
Unconstrained 5G MBB penetration	38.1%	76.0%	2.0x	E1u = E1/PC2	For simplicity, we assume no impact of coverage on usage per capita
Unconstrained FWA penetration	1.8%	4.5%	2.5x	A2u = A2 / PC1	
Unconstrained 4G FWA penetration	0.9%	0.2%	0.2x	B2u = A2u - E2u	
Unconstrained 5G FWA penetration	0.9%	4.3%	4.8x	E2u = E2/PC2	
Unconstrained IoT devices per capita	0.38	0.66	1.7x	A3u = A3/PC1	
Capacity suppression factor	**2023**	**2030**	**Multiple**	**Calculation**	**Comments**
% data consumption lost due to congestion	15.1%	10.9%	0.7x	%C	2023: based on Huawei data; 2030: Coleago assumption[1]
Capacity suppression factor	0.85	0.89	1.0x	CSF = 1 - %C	A CSF of 1 would imply no congestion
Usage per connection if CSF were 1	**2023**	**2030**	**Multiple**	**Calculation**	**Comments**
Unconstrained 4G MBB usage per SIM	20.9	33.4	1.6x	C1u = C1/CSF	We assume for simplicity that congestion affects traffic but not aoption
Unconstrained 5G MBB usage per SIM	25.8	76.0	2.9x	F1u = F1/CSF	
Unconstrained 4G FWA usage per SIM	255.3	283.8	1.1x	C2u = C2/CSF	
Unconstrained 5G FWA usage per SIM	315.0	646.8	2.1x	F2u = F2/CSF	
Unconstrained IoT usage per device	0.8	4.2	5.0x	B3u = B3	We assume (conservatively) that congestion does not affect IoT

[1] *Note: for 2030, we assume that congestion halves in each market linearly over 10 years. On a global blended level, our calculations take a weighted average congestion for Developed and Emerging markets respectively, based on data supplied by Huawei for 2023.*

TDI calculations – Unconstrained demand

MBB demand	2023	2030	Multiple	Calculation	Comments
Total MBB SIM penetration	96.1%	101.8%	1.1x	A1u	
4G penetration (SIMs per capita)`	58.0%	25.8%	0.4x	B1u	
4G usage per SIM (GB/month)	20.9	33.4	1.6x	C1u	
4G usage per capita (GB/month)	12.1	8.6	0.7x	D1u = B1u×C1u	
5G penetration (SIMs per capita)`	38.1%	76.0%	2.0x	E1u	
5G usage per SIM (GB/month)	25.8	76.0	2.9x	F1u	
5G usage per capita (GB/month)	9.8	57.8	5.9x	G1u = E1u×F1u	
Total MBB usage per capita (GB/month)	22.0	66.4	3.0x	H1u = D1u + G1u	
Population growth factor (2023=100%)	100%	105%	1.1x	P	
Total MBB usage per 2023 capita (GB/month)	22.0	69.9	3.2x	T1u = H1u×P	
MBB index	**80.0**	**254.5**	**3.2x**	I1u = T1u×Nu	Indicates traffic trend

FWA demand	2023	2030	Multiple	Calculation	Comments
Total FWA SIM penetration	1.8%	4.5%	2.5x	A2u	
4G penetration (SIMs per capita)`	0.9%	0.2%	0.2x	B2u = A2u - E2u	
4G usage per SIM (GB/month)	255.3	283.8	1.1x	C2u	
4G usage per capita (GB/month)	2.4	0.6	0.3x	D2u = B2u×C2u	
5G penetration (SIMs per capita)`	0.9%	4.3%	4.8x	E2u	
5G usage per SIM (GB/month)	315.0	646.8	2.1x	F2u	
5G usage per capita (GB/month)	2.8	27.5	9.8x	G2u = E2u×F2u	
Total FWA usage per capita (GB/month)	5.2	28.1	5.4x	H2u = D2u + G2u	
Population growth factor (2023=100%)	100%	105%	1.1x	P	
Total FWA usage per 2023 capita (GB/month)	5.2	29.6	5.7x	T2u = H2u×P	
FWA index	**18.9**	**107.8**	**5.7x**	I2u = T2u×Nu	Indicates traffic trend

IoT demand	2023	2030	Multiple	Calculation	Comments
Total IoT devices per capita	0.38	0.66	1.7x	A3u	
GB/month per device	0.8	4.2	5.0x	B3u	
IoT traffic per capita (GB/month)	0.3	2.8	8.7x	D3u = A3u×B3u	
Population growth factor (2023=100%)	100%	105%	1.1x	P	
Total IoT traffic per 2023 capita (GB/month)	0.3	2.9	9.1x	T3u = D3u×P	
IoT index	**1.2**	**10.7**	**9.1x**	I3u = T3u×Nc	Indicates traffic trend

Total mobile data demand	2023	2030	Multiple	Calculation	Comments
Total traffic per 2023 capita (GB/month)	27.4	102.4	3.7x	Tu =T1u +T2u +T3u	
Normalisation factor	3.6	3.6		Nu = 100/Tu(2023)	
TDI (constrained)	**100.0**	**373.0**	**3.7x**	TDIu	Indicates total traffic trend

Appendix B

Overview of IMT bands

Overview of IMT bands (1)

Band	Name	Duplex	FDD UL (MHz)	FDD DL (MHz)	TDD (MHz)	BW (MHz)	ITU R1 (MHz)	ITU R2 (MHz)	ITU R3 (MHz)	Comments
31	450MHz	FDD				10				Very good propagation but limited bandwidth, weak ecosystem and requires large antennas. Specifications defined for 4G only. Some potential for wide-area IoT (e.g.
72	450MHz	FDD				10				
73	450MHz	FDD				10				
n71	600 US DD	FDD	663-698	617-652		70		70 in some	70 in some	5G low-band in ITU R2 and R3; used for Digital Terrestrial TV broadcast in ITU R1, potential future low-band IMT resource
n29	700 SDL	SDL		717-728		10		some		
n12	700 lower	FDD	699-716	729-746		30		30 in some		5G candidate band ITU R1; quasi global harmonisation, can be used for 4G and 5G
n14	700 upper	FDD	788-798	758-768		20		20 in some		
n28	APT 700	FDD	703-748	758-803		90	60		90	Originally 4G band in ITU R2 and R3; quasi-global harmonisation; 5G candidate band ITU R1; quasi global harmonisation, can be used for 4G and 5G; 20MHz centra gap auctioned as SDL in some European countries, growing operator interest
n20	800	FDD	832-862	791-821		60	60		60	Original ITU R1 DD band for 4G
n18	lower 800 Japan	FDD	815-830	860-875		30				
n5	850	FDD	824-849	869-894		50		50	some	Original 2G in ITU R2 and R3
n8	900	FDD	880-925	925-960		70	70	some	70	Original 2G in ITU R1, partially used for 3G; refarming to 5G
n51	L-Band extension	TDD			1427-1432	5				
n76	Ext. L-Band EU	SDL		1427-1432		5		some		
n50	L-Band	TDD			1432-1517	85			85	Good propagation and growing ecosystem
n75	L-Band EU	SDL		1432-1517		85	85	85		
n74	1500 lower L-Band	FDD	1427-1470	1475-1518		80				
n3	1800	FDD	1710-1785	1805-1880		150	150		150	Prime international 4G resource, ITU R1 and R3
n39	1900 gap	TDD			1880-1920	40			40	
n2	PCS	FDD	1850-1910	1930-1990		120		120 in some		
n25	Extended PCS	FDD	1850-1915	1930-1995		130		130 in some		
n70	AWS 4	FDD	1695-1710	1995-2020		40		40 in some		
n34	2100 TDD	TDD			2010-2025	15				Limited bandwidth and ecosystem; no 5G roadmap
n1	IMT	FDD	1920-1980	2110-2170		120	120	120	120	Original 3G band; refarming to 4G and 5G
n65	Extended IMT	FDD	1920-2010	2110-2200		180				
n66	Extended AWS	FDD	1710-1780	2110-2200		160		140		
n40	S-band	TDD			2300-2400	100	40	100	90	Good ecosystem, but more limited bandwidth in ITU R1
n30	2300	FDD	2305-2315	2350-2360		20				

Overview of IMT bands (2)

Band	Name	Duplex	FDD UL (MHz)	FDD DL (MHz)	TDD (MHz)	BW (MHz)	ITU R1 (MHz)	ITU R2 (MHz)	ITU R3 (MHz)	Comments
n41 / n90	2600 TDD	TDD			2496-2690	190	190 in some	190 in some	190 in some	Most ITU R1 splits 2600MHz in TDD and FDD; unified in e.g. China, some other APT countries, African countries (see main report for extra commentary)
n90	2500 BRS	TDD			2496-2690	190				
n38	2600 TDD	TDD			2570-2620	50	40 others	40 others	40 others	
n7	2600 FDD	FDD	2500-2570	2620-2690		140	140 others	140 others	140 others	
n77	C-Band	TDD			3300-4200	900	400	400	400	3400-3800MHz main 5G capacity band, excellent ecosystem support
n48	CBRS	TDD			3550-3700	150				
n79	C-Band	TDD			4400-5000	600	some	some	some	Some existing allocations (e.g. 200MHz in China, 190MHz in Russia)
n96	6 GHz	TDD			5925-7125	1200				
n81	900 SUL	SUL	880-915			35				
n82	800 SUL	SUL	832-862			30				
n83	APT 700 SUL	SUL	703-748			45				
n80	1800 SUL	SUL	1710-1785			75				
n84	2100 SUL	SUL	1920-1980			60				
n86	Ext AWS SUL	SUL	1710-1780			70				
n95	2100 SUL	SUL	2010-2025			15				
n257	28GHz	TDD			26500-29500	3000				
n258	26GHz	TDD			24250-27500	3250	2000	3200	3250	Being considered in ITU R2 and R3 in particular, with assignments in some countries completed or planned
n260	39GHz	TDD			37000-40000	3000				
n261	28GHz	TDD			27500-28350	850			850	

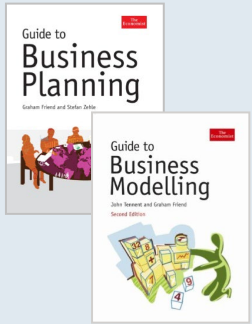
Appendix C

About Coleago Consulting

A powerful combination of skills and experience

Coleago is focused purely on the telecoms industry.

Books authored by Coleago's founders



Guide to Business Planning named Outstanding Academic Title 2009
The Guide to Business Planning, which recently appeared in its 2nd edition, was named as one of the "Outstanding Academic Titles, 2009 (Business and Economics)" by Choice, the US academic review journal. Source: Choice, 5th January 2010.

Telecoms project experience on all continents

- Founded in 2001, Coleago delivers a rare combination of telecoms related commercial and technical skills and experience. Our expertise has been developed exclusively within the telecoms sector. Since 2001, we have delivered small and large projects in around 75 countries in both developed and emerging markets on all continents.
- Our team includes marketing and commercial experts, technical experts, telecoms finance professionals and telecoms regulatory experts. Leveraging experience from previous projects, Coleago can deploy a small team of experts to deliver a consulting project reliably, quickly and cost effectively.

Industry thought leadership

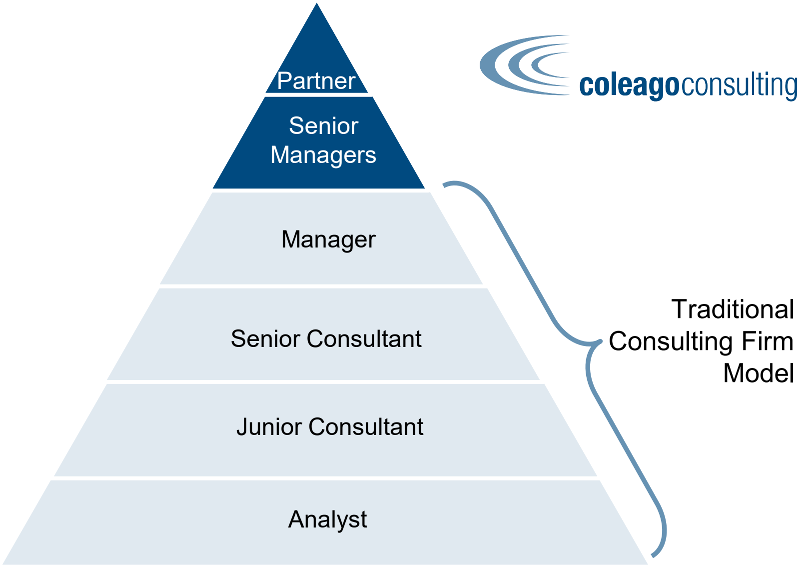
- Coleago is sought after by the GSMA and has delivered several projects for the GSMA on spectrum and policy related matters as well as the connected societies programme. The GSMA and the European Commission employed Coleago for *Best Practice in Spectrum Assignment* workshops.
- Coleago consultants regularly speak at international telecoms conferences, on topics such as spectrum, infrastructure sharing, digital content in Europe, Asia, the Americas and Africa.
- We are delivering training and leadership development programmes to the telecoms industry, such as the Telecoms Mini-MBA, the Mobile Operator War Game, executive coaching, regulatory capacity building, and best practice in infrastructure sharing.

Exceptional business planning expertise

- Coleago's consulting team has been developing telecoms business plans since 1994.
- Stefan Zehle and Graham Friend are the co-authors of the award winning *The Economist's Guide to Business Planning.*

Experience based consulting approach

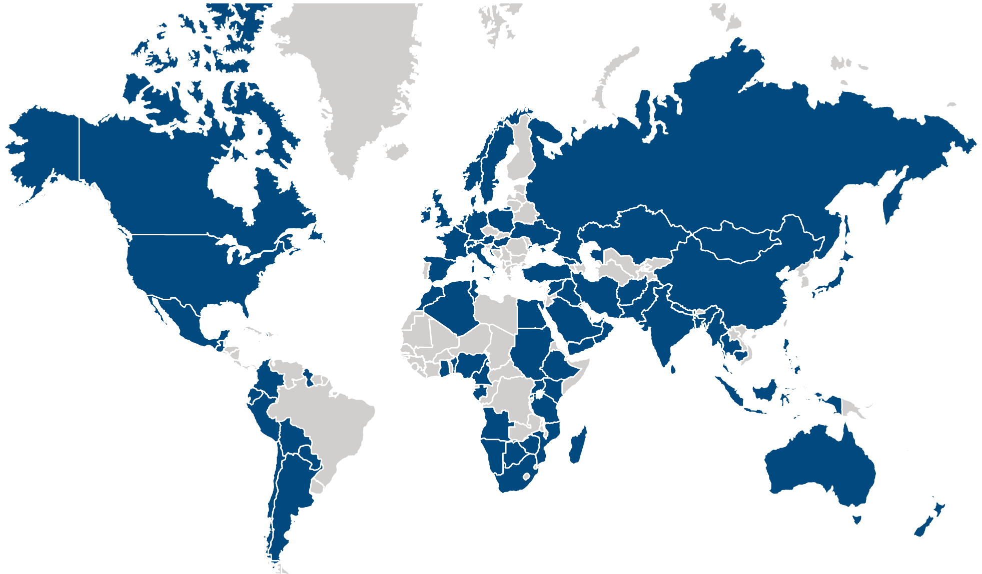
- We do not use inexperienced associates or analysts – all our consultants have a minimum of 15 years' experience and most have over 20 years, often at board level in operational businesses.
- Our insight and advice is therefore based on practical experience and proven processes and methodologies developed over many years. Clients can be confident that their project will be delivered by partner and senior manager level consultants from start to finish, and our solutions and recommendations will be credible, relevant, realistic and practical.



Since its foundation in 2001, Coleago has carried out projects in over 60 countries

Coleago's clients include telecoms regulators, fixed and mobile operators, MVNOs, equipment vendors, and content providers.

African Export-Import Bank, Egypt - Airtel, Kenya - Airtel, Burkina Faso - Airtel, Uganda - Airtel International, Netherlands - América Móvil, S.A.B. DE C.V, Mexico - AMTA, Australia - Axiata Group, Malaysia - Banglalink, Bangladesh - Base, Belgium - Beeline, Russia, Kazakhstan - Belgacom, Belgium - Blyk, UK - Botswana Telecommunications Authority, Botswana - BT, UK - Cable Bahamas, Bahamas - Canada Posts, Canada - Cell C, South Africa - Celcom, Malaysia - Celtel International, Oman - Cincinnati Bell, USA - Centrica, UK - Claro, Chile - Claro, Peru – Claro, El Salvador - Claro, Colombia CRASA, Botswana - Dialog, Sri Lanka - DiGi, Malaysia - Digicel, Haiti - DMC, Cambodia - dtag, Thailand - Econet, Zimbabwe - Ericsson, Indonesia - Etisalat, Nigeria - European Commission, EU - EE, UK - Hellenic Telecommunications and Post Commission (EETT), Greece - Fair Trading Commission, Barbados - Gibraltar Regulatory Authority, Gibraltar - Grameenphone, Bangladesh - GSMA, UK, China, Kenya, Tanzania, Benin, India, Bangladesh, Indonesia - Huawei, China, Europe, Kazakhstan, South Africa, Colombia - Hutchison 3, UK, - Hutchison 3, Indonesia - Idea Cellular, India - Indosat Ooredoo, Indonesia - ITU, Switzerland - Kabel NRW, Germany - Karoui & Karoui International, Tunisia - Kyivstar, Ukraine - KPN, Austria, France, Luxembourg, Switzerland - JCRA, Jersey - Kistefos, Norway - Malta Communications Authority, Malta - Maxis, Malaysia - Ministry of Transport and Communications, Myanmar - Mobicom, Mongolia - Mobilink, Pakistan - MTN Group, South Africa - MTN, Ghana - MTN, Nigeria - MTN, Uganda – MTN, Afghanistan - MTN, Cameroon - National Communications Authority, Ghana -

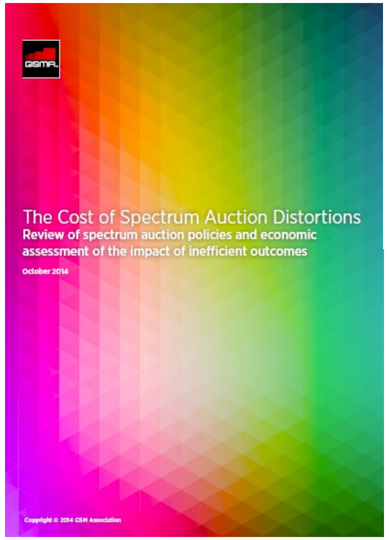


Netia, Poland - New Century GlobalNet, Japan - Ncell, Nepal - Noor, Tunisia - Ofcom, UK - Omantel, Oman - Ooredoo Group, Qatar - Ooredoo Algerie, Algeria - Ooredoo, Iraq - Ooredoo, Maldives - Ooredoo, Myanmar - Indosat Ooredoo, Indonesia - Optus, Australia - Orange, UK - Orange, Switzerland - Orange, Poland - Orange, South Africa - o2, Ireland - o2, UK - P4, Poland - Pakistan Mobile Communications Ltd, Pakistan - PT Bandung Talent Source, Indonesia - Robi Axiata, Bangladesh - Rogers, Canada - Sabafon, Yemen - Sentech, South Africa - SETAR, Aruba - SFR, France - Smart Axiata, Cambodia - Smart, Philippines - Smartfren, Indonesia - Sunrise, Switzerland – T2, Slovenia - TASC Towers, UAE - Tata Communications, India - Telecom Argentina Personal, Argentina - Telecom Personal, Paraguay – Telekom Slovenije, Slovenia - Telefonica, Spain - Telecommunications Agency, Guyana - Telkom, Indonesia - Telkomsel, Indonesia - TelOne, Zimbabwe - Trilogy International, Bolivia - Tunisie Telecom, Tunisia - Telenor Group, Norway - Telenor, Malaysia - Telenor, Denmark - Telenor, Hungary - Telenor Thailand - Televisa, Mexico - Telma, Madagascar - Tigo, Paraguay, Guatemala, Colombia - Tuaropaki Trust, New Zealand – Umniah, Pakistan - UK Broadband, UK - U-Mobile, Malaysia - Veon, Netherlands, Italy - Viettel, Cambodia, Tanzania - VIP-Net GSM, Croatia - Viva, Bahrain - Vodafone, UK - Vodafone, Germany - Vodafone, Hungary - Vodafone, Egypt - Vodafone, Ghana XL Axiata, Indonesia – Warid Group, UAE, Georgia, Cameroon - Warid, Pakistan - Wataniya, Kuwait - WOM SA, Chile - World Bank/IFC, Angola, Ethiopia - Zain, Saudi Arabia - Zain, Sudan - 2degrees Mobile, New Zealand

A sample of Coleago reports in the public domain

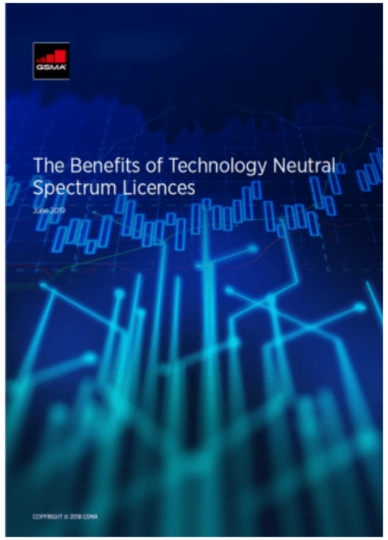
Report on Coleago spectrum demand model for the GSMA to estimate mid bands spectrum demand for 5G as an input to the WRC-23.

Meeting low band needs requires long-term planning from policymakers. low band spectrum is the cornerstone of digital equality and a driver of broad and affordable connectivity. This Coleago report for the GSMA was published in June 2022.



The cost of spectrum auction distortions, a Coleago report for the GSMA to highlight how flawed spectrum auction rules result in inefficient outcomes and adverse consequences for a country's economy

Sustainable spectrum pricing, providing policy makers with a methodology to assess spectrum pricing, taking account of the increased spectrum needs for 5G without endangering operator's ability to deliver the 5G vision.



The benefits of technology neutral spectrum licences, a Coleago report for the GSMA showing clear evidence that technology neural spectrum licences produce benefits for mobile services development and efficient use of spectrum.

Mobile Services, Spectrum and Network Evolution to 2025, a review for telecoms regulators and operators of global developments, insights, trends, and best practices, to inform spectrum policy and management and operator strategies

Glossary

3GPP	3rd Generation Partnership Project.
5GC	5G Core Network.
AI	Artificial Intelligence (machine learning).
API	Application Protocol Interface.
APT	Asia Pacific Telecommunity.
AR	Augmented reality. Also see MR, VR, XR.
ARPU	Average Revenue per Unit.
AUPU	Average Usage per Unit or per User.
BS, BTS	Base (Transceiver) Station
CA	Carrier Aggregation.
CAGR	Compound Annual Growth rate.
Capex	Capital Expenditures (investments).
CS	Consumer Surplus (welfare).
D2D	Direct to device (satellite communications).
D&A	Depreciation and Amortisation.
DL	Downlink.
DSS	Dynamic Spectrum Sharing (allows bandwidth in a given to be allocated between different technologies such as 4G and 5G).
EB	Exabyte (= 1000 petabytes, 1 million terabyte, 1 billion gigabytes).
EBITDA	Earnings Before Interest, Tax, Depreciation and Amortisation.
eMBB	Enhanced Mobile Broadband.
eMTC	Enhanced Machine Type Communications.
EPC	Enhanced Packet Core.
FBB	Fixed Broadband.
FCC	US Federal Communications Commission.
FDD	Frequency Division Duplex. In FDD mode, half of the bandwidth is allocated to uplink, half to downlink. Hence the notation 2x20 MHz for a 20 MHz 'paired' channel. Also see TDD.
FR1, FR2	Frequency Range 1 (bands below 6GHz) and Frequency Range 2 (mm waves).
FWA	Fixed Wireless Access.
GB	Gigabyte
Gbps	Gigabit per second
GSA	Global Mobile Suppliers Association.
HAPS	High Altitude Platform Station.
HD	High Definition (video).
IMT	International Mobile Telecommunications.
IP	Internet Protocol.
IoT	Internet of Things: machine-to-machine or "machine-type" communications via the Internet, mediated by fixed and/or wireless networks.
ITU	International Telecommunications Union.
JV	Joint Venture.
LEO	Low Earth Orbit (satellite).
M2M	Machine-to-machine (see IoT).
MBB	Mobite Broadband.
Mbps or Mbit/s	Megabits per second (a measure of network throughput).
MIMO	Multiple Input / Multiple Output antenna system; e.g. 2T2R (meaning two transmit and 2 receiver antennas on the site), which is the base MIMO configuration for 4G and 5G, also referred to as "order 2" or "2x2" MIMO.
mMIMO	Massive MIMO (typically 32x32 or 64x64 order MIMO).
mmWave or MW	Millimetre Waves or Microwave (spectrum).
MNO	Mobile Network Operator.
MR	Mixed reality. Also see AR, VR, XR.
NR	New Radio (5G).
NSA	Non Stand-Alone (5G).
NTN	Non-terrestrial networks.
OFDM	Orthogonal Frequency Division Multiplexing.
Opex	Operating Expenditures (recurring or 'running' costs).
O-RAN	Open RAN Alliance (not to be confused with "Open RAN")
PIM	Passive Inter-Modulation (PIM products degrade air-interface performance).
PPDR	Public Protection and Disaster Relief.
QAM	Quadrature Amplitude Modulation.
QPSK	Quadrature Phase Shift Keying.
RAN	Radio Access Network. Includes radio sites and backhaul transmission (but not the core network).
RF	Radio Frequency (e.g. RF unit).
RIC	RAN Intelligent Controller.
ROIC	Return on Invested capital.
RRU	Remote Radio Unit.
SA	Stand-Alone (5G).
SD	Standard Definition video.
SDL	Supplementary Downlink.
SLA	Service Level Agreement.
TDD	Time Division Duplex. Also see FDD. Spectrum in TDD mode allows for asymmetric allocation of uplink and downlink resources, yielding greater overall spectral efficiency.
TCO	Total Cost of Ownership (annualised).
U6G	Upper 6GHz spectrum band.
UE	User Equipment.
UHD	Ultra High Definition video.
UL	Uplink.
uRLLC	Ultra Reliable Low Latency Communications.
VR	Virtual Reality. Also see AR, MR, XR.E2
XR	Encompasses Augmented Reality (AR), Mixed reality (MR), Virtual reality (VR)
WACC	Weighted Average Cost of Capital.