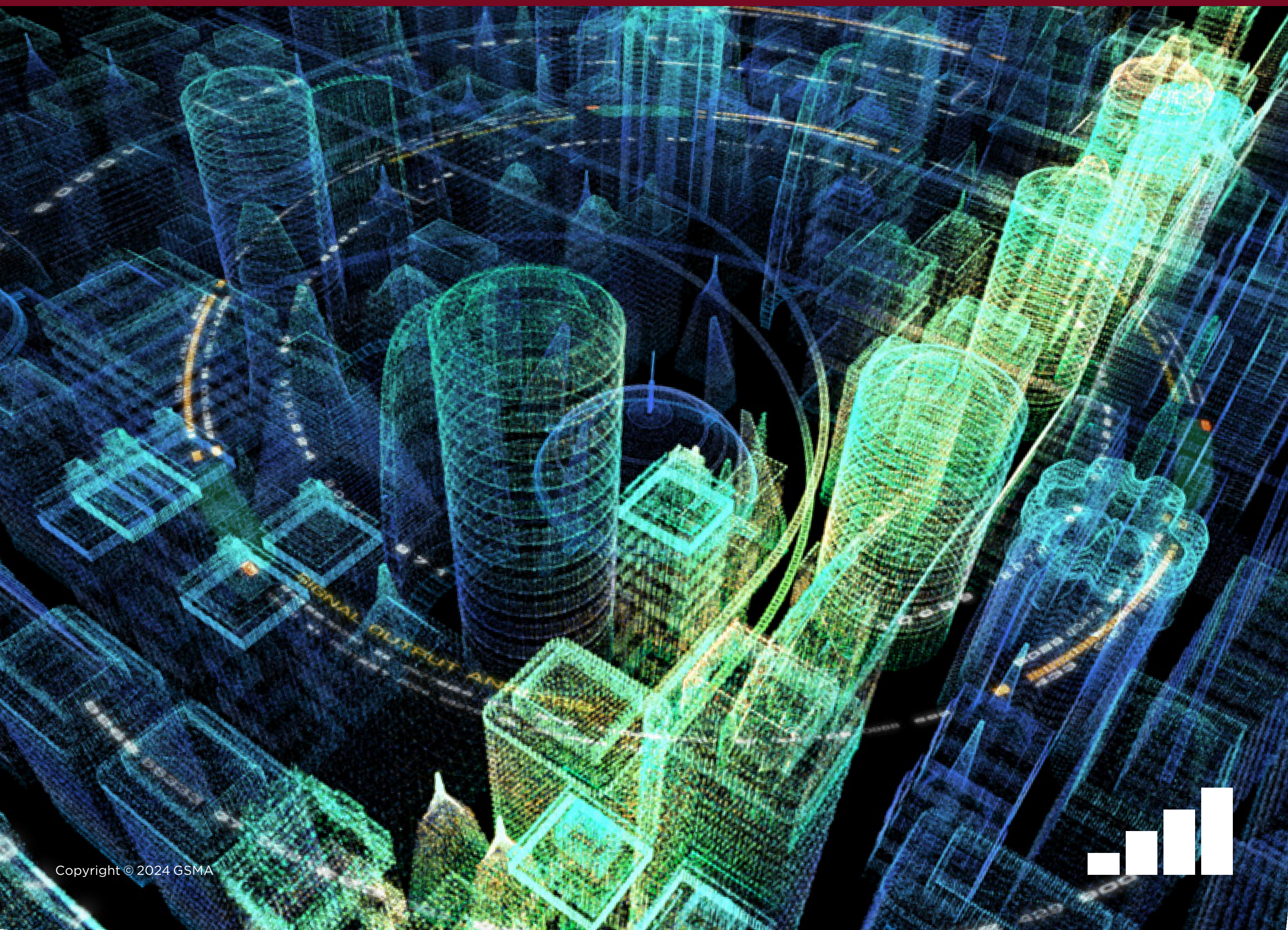
The Impact of Spectrum Set-Asides on Private and Public Mobile Networks

May 2024



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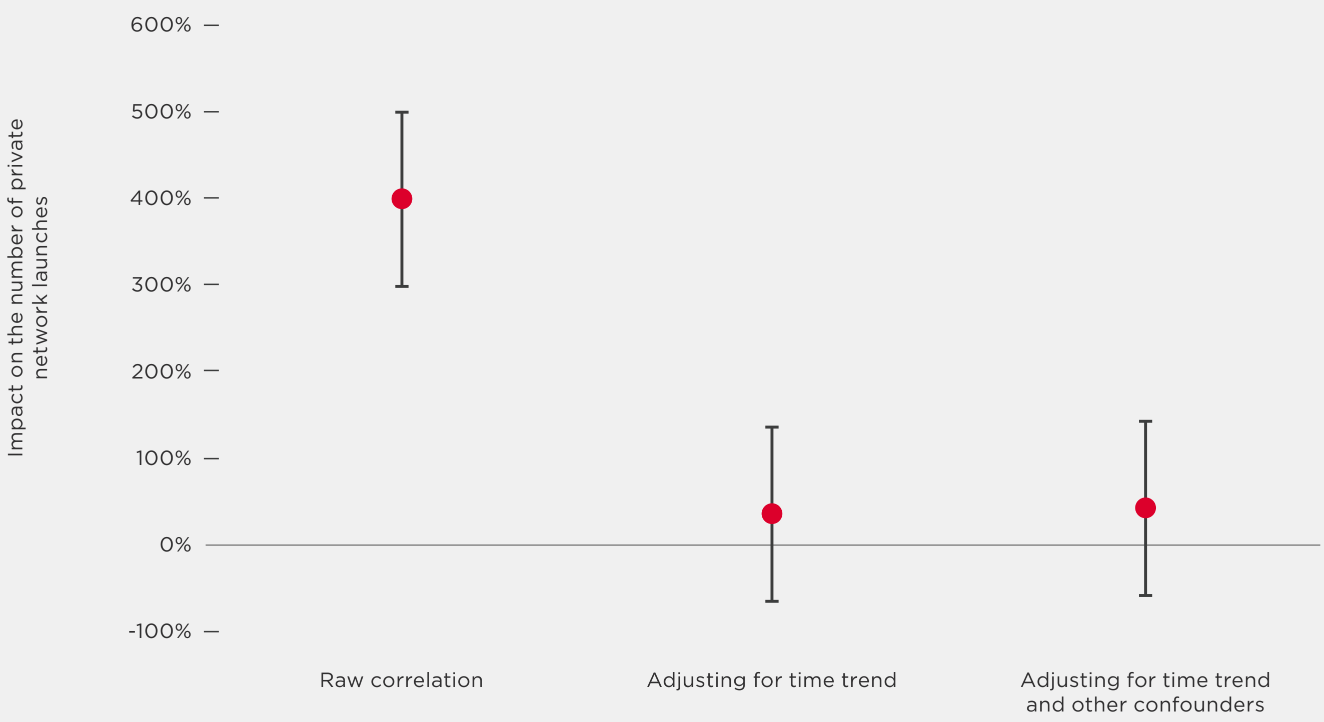
Executive summary

When considering all relevant variables, there is no indication that the introduction of set-asides has led to an increase in the adoption of private networks.

Association between spectrum set-asides and the number of private network customer launches



Source: GSMA Intelligence analysis

1. Networks need to keep up with the demands of cutting-edge services and their use cases

The digitalisation of enterprises offers the promise of substantial gains in productivity. Policymakers are therefore seeking to promote the digital transformation of industries. Their efforts are focused on delivering the network infrastructure of the future. Advanced industrial use cases require wireless connectivity that delivers high bandwidth, low latency, extremely high reliability and enhanced security.

5G caters to these needs by design, offering support for digital solutions such as massive IoT communications, cloud storage and computing, and AI. For businesses, the primary route to 5G solutions is the public network operators and their end-to-end offerings, including access to shared public infrastructure and operator-managed spectrum. In some instances, enterprise users may require solutions tailored to their particular needs. Private 5G networks can address this through custom design to meet the desired performance level and demand for services.

2. There are various options to make spectrum available as regulators look to foster network infrastructure development

Just like their public counterparts, private wireless networks require radio spectrum to operate. Given the interest in private networks, regulators are examining different options to enable access to spectrum by industries. These include spectrum sharing frameworks, leasing obligations attached to licences for public network operators, and spectrum set-asides that reserve spectrum for potential industry use. Each option offers particular advantages and disadvantages, as examined in a previous GSMA study.[1]

This analysis examines the impact of spectrum set-asides. On the one hand, set-asides provide certainty of access and tenure for enterprises, potentially incentivising private network adoption and digitalisation. On the other hand, set-asides reduce the amount of spectrum available for public networks. Lower amounts of spectrum can restrict throughput of public networks or make their construction and operation more costly, resulting in a lower quality of service.

Set-asides therefore present a trade-off. Until now, there has been no empirical evidence available on the magnitude of each effect. This research addresses the evidence gap through robust statistical analysis on both sides of this trade-off.

3. Analysis of the impact of set-asides shows no evidence of a positive effect on the digitalisation of enterprises

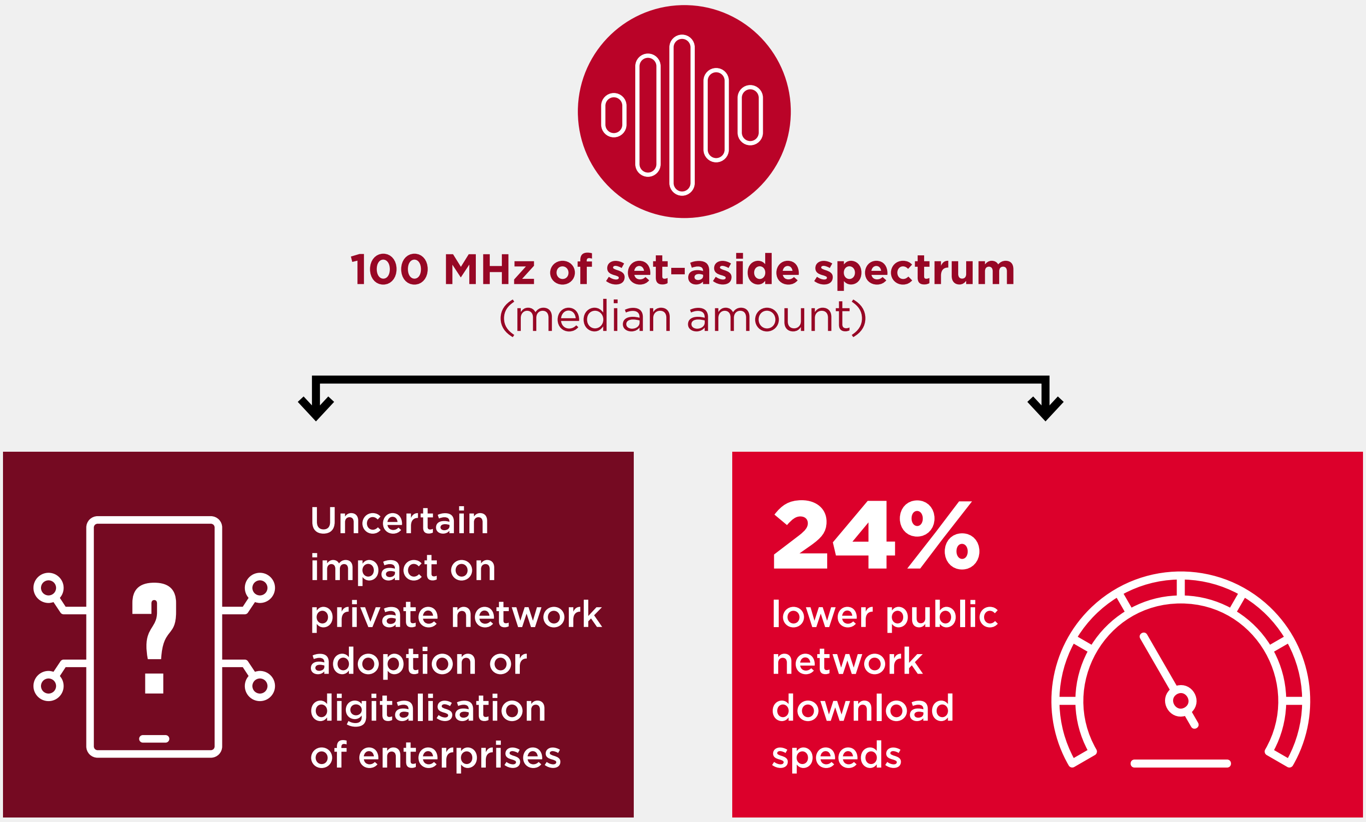
The analysis finds no indication that spectrum set-asides can accelerate the digitalisation of enterprises. This is consistent whether we examine the impact of set-asides on either the adoption of private networks or IoT connectivity by enterprises. Any apparent association between set-asides and the adoption of private networks or IoT can be explained by time trends and other factors. These time trends and factors, known as confounders, have independently affected adoption of set-asides and adoption of private networks, leading to an apparent correlation between the two variables. However, any initial correlations are spurious and not indicative of a policy effect.

The lack of association between set-asides and the adoption of private networks can be explained by the availability of alternative options for spectrum access. Enterprises can access complete private network solutions (including spectrum) from public mobile network operators. A further option for enterprises is to power their private networks using spectrum available through sharing frameworks or spectrum leasing. Similarly, the lack of association with IoT adoption indicates that set-asides do not enhance the ability of enterprises to access these services beyond what alternative spectrum access modes offer.

Examining the other side of the trade-off, this analysis finds that the amount of spectrum available to public mobile networks impacts network quality. An additional 100 MHz of spectrum was associated with download speeds that are 24% higher (equivalent to 4.5 Mbps in terms of average global download speeds between 2014 and 2022). A median set-aside amount of 100 MHz can therefore have a substantial negative impact on consumers and enterprises using public networks. As quality of public mobile networks has been widely linked to economic benefits, a clear economic cost emerges.

1. The Impact of Spectrum Set-Asides on 5G, GSMA, 2023

Figure 1
Impact of set-asides



Source: GSMA Intelligence

4. **Policymakers should be wary of simple correlations and one-sided analysis that can overlook the indirect and unintended consequences of set-asides**

   The results of this study highlight the need to consider the unintended and undesired consequences of spectrum set-asides, particularly as there is no evidence of a clear benefit. We advise caution in relying on spectrum set-asides as a framework for access. Set-asides for enterprises may not be the most economically efficient assignment of spectrum compared to the other options available. Alternative spectrum access frameworks should be considered and prioritised in the first instance.

   Offering set-aside spectrum at reduced or no cost can also lead to distorted incentives in the market for digital solutions and infrastructure. Pricing spectrum differently depending on whether it is used by public or private networks impacts the relative cost of each solution. As the cost saving is passed on to prospective users, the use of private networks with set-aside spectrum is effectively subsidised. This can put solutions based on public mobile networks at a disadvantage when they otherwise would have been the optimal choice, leading to economic inefficiency.

   While the evidence of this study provides early insight into the impact of set-asides, emerging evidence on the impacts of different spectrum access frameworks should be continuously evaluated. Policy decisions should be re-evaluated as new evidence and technological solutions emerge. In particular, we note the need for better and harmonised international data on the adoption of digital technologies by enterprises.

1. The digitalisation of enterprises: 5G infrastructure and spectrum options

1.1 Meeting the needs of digitalised industries with wireless infrastructure

The digitalisation of enterprises is set to bring the next wave of productivity growth. As well as 5G-enhanced connectivity, enterprises have been widely adopting digital services such as cloud storage and computing, IoT, machine-to-machine connectivity, and security services.[2] Applications such as these will enable further automation and the integration of smart devices into enterprise infrastructure.

Modern network infrastructure is a key pillar supporting this digital revolution in the business sector. Infrastructure underpins the transmission of an ever-growing amount of data. This data is critical to the operation of productivity-increasing technological solutions embedded in production lines, electricity grids, smart city infrastructure and other aspects of digitalised industries.

A policy objective for many governments is to foster the digitalisation of enterprises and focus on the network infrastructure needed. To realise all the prospective benefits of digitalisation, network infrastructure requires specific capabilities to support enterprise use cases and digital services. 5G technology offers a range of these capabilities (Table 1).

Table 1
5G connectivity features and enterprise use cases

5G connectivity feature	Example enterprise use cases
High-bandwidth wireless	Computer vision for manufacturing production lines
Ultra-reliable, low-latency communications (URLLC)	Autonomous and automated vehicles VR and AR, including healthcare applications
Massive machine-type communications (IoT)	Sensor networks powering smart cities (traffic lights, air quality, traffic monitoring)
Highly-secure, on-premises data processing	Quality control for production lines Highly-secure data transmission for contract manufacturers (defence and other strategic industries)

Source: GSMA Intelligence

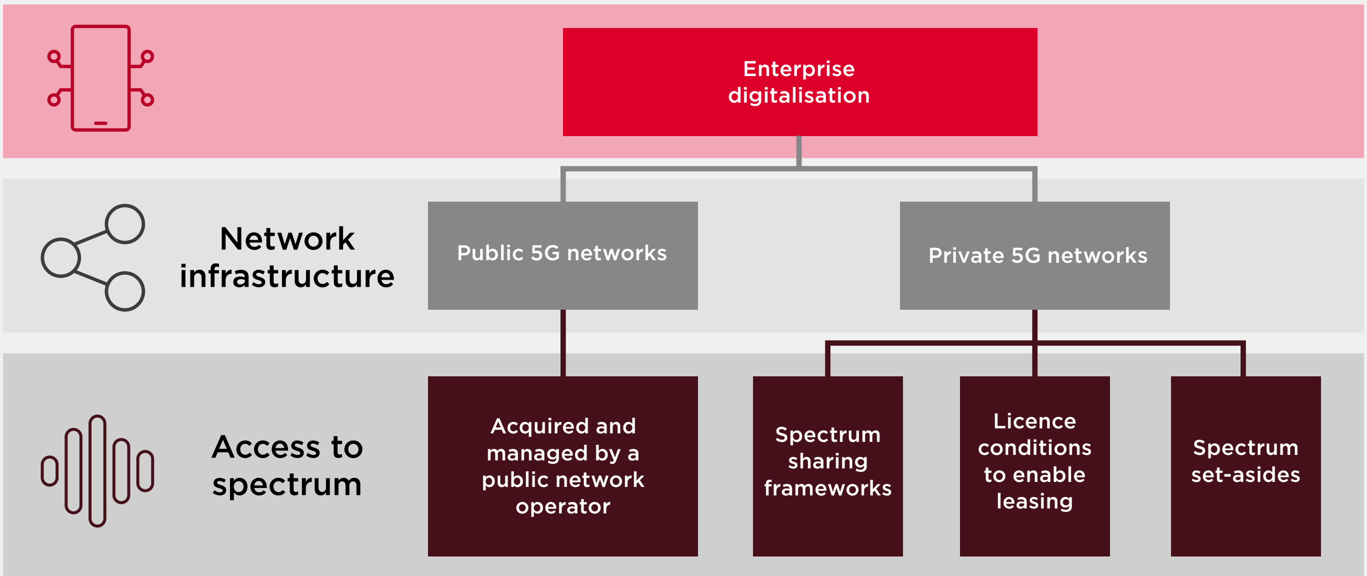
2. Enterprise Opportunity 2024: operator strategies, plans and expectations, GSMA Intelligence, 2024

1.2 Options to provide 5G solutions to enterprises

To foster wireless networks, policymakers need to manage radio spectrum efficiently, with an aim to deliver the greatest economic value from its use across technologies and stakeholders.

For most enterprises, the default option for 5G solutions is public mobile network operators and their end-to-end solutions, including access to shared public infrastructure and managed spectrum (Figure 2). Depending on the local availability of mobile services and particular conditions, such as in industrial locations, some enterprises have connectivity needs that may not be universally served by public mobile networks. This can spur interest in custom, private mobile networks. However, private 5G-based connectivity generates additional demand for radio spectrum. Policymakers therefore need to consider these needs and options for enabling access to spectrum for enterprises.

Figure 2
Options to provide 5G solutions to enterprises



Source: GSMA Intelligence

Among the spectrum access options for private enterprise networks are the following:[3]

- **setting spectrum aside for industrial use**, permitting its local use on the basis of applications from enterprises
- **creating shared spectrum bands**, enabling several users to access spectrum simultaneously under a set of priority-of-access rules, including support for private mobile networks
- **stipulating licence conditions for public mobile network operators**, requiring them to deploy private networks or lease spectrum to enterprises.

Each of these options comes with potential costs and benefits to industry users and consumers. Details of these have been analysed in a previous GSMA study.[4]

3. The Impact of Spectrum Set-Asides on 5G, GSMA, 2023
4. The Impact of Spectrum Set-Asides on 5G, GSMA, 2023

1.3 Spectrum set-asides: a policy trade-off

The cost-benefit elements of setting aside spectrum comprise:

- the potential benefits for industry users – these include improved ease of accessing spectrum, which could eventually lead to greater adoption of innovative applications in enterprises and productivity gains
- the potential opportunity cost of set-asides – as set-asides reduce spectrum availability for public networks, they can come with negative effects on the quality and availability of public network service, network investment and retail prices.

Despite grounded theoretical considerations on the benefits and costs, empirical evidence on the impact of set-asides is lacking. Previous analyses have drawn loose associations between set-aside policy and the adoption of private networks.[5,6] So far, no studies have established evidence on the cause and effect relationship between set-asides and digitalisation, underscoring the need for robust empirical research to inform policy decisions.

Against this backdrop of uncertainty, the key question is whether spectrum set-asides for enterprises can be justified in pursuit of greater enterprise digitalisation – at the expense of limiting the growing capacity needs of public mobile networks.

This study assesses this question in two parts:

- the benefits of set-asides and their relationship with indicators of enterprise digitalisation (Chapter 2)
- the opportunity cost of set-asides, measured by the effect of the amount of spectrum for public mobile networks on the speeds experienced by consumers (Chapter 3).

5. Market study: private wireless networks using 4G or 5G, Australia Communications and Media Authority, 2023
6. Private Mobile Networks: Member report February 2024, GSA, 2024

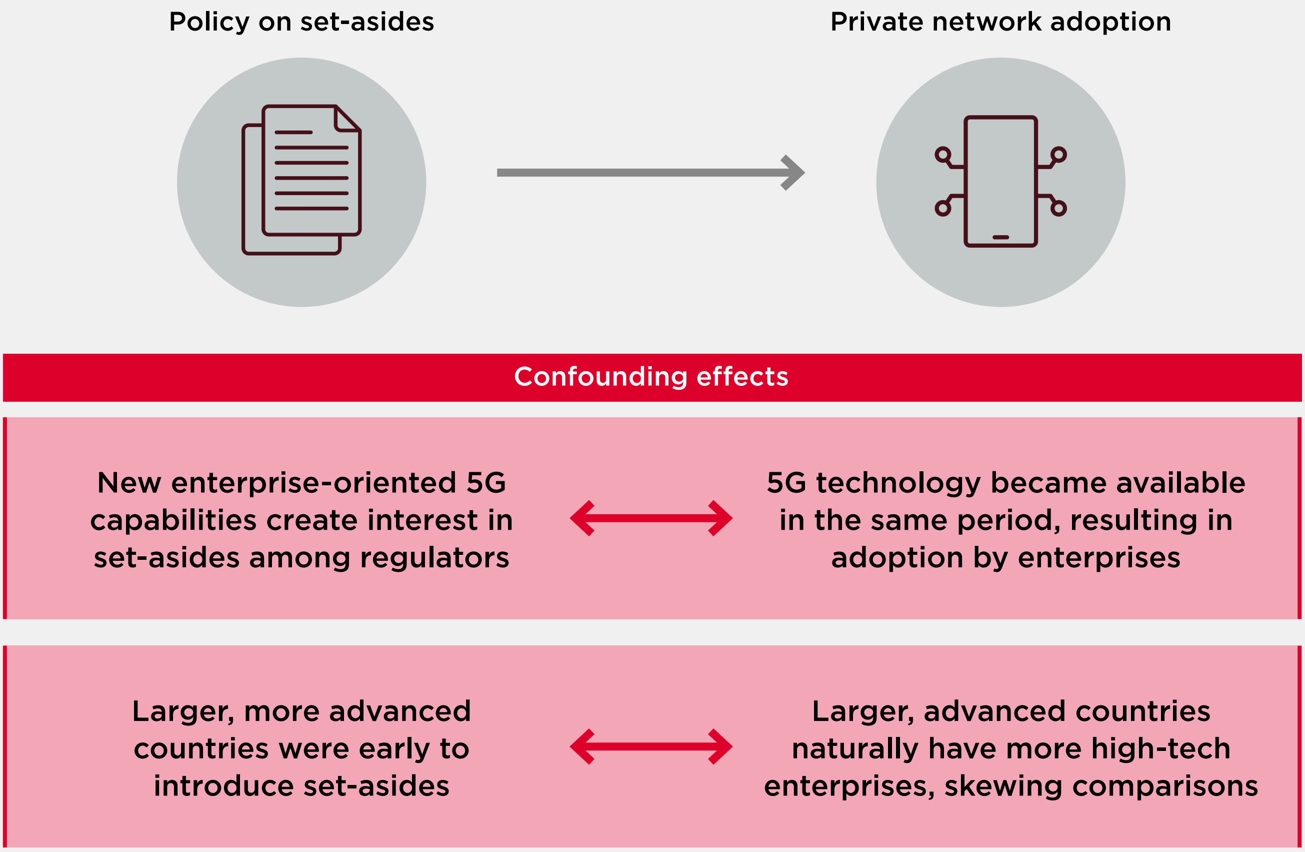
2. Do set-asides accelerate the digitalisation of enterprises?

2.1 Measuring the cause-and-effect relationship between set-asides and digitalisation

Measuring the impact of set-aside policy entails identifying the cause-and-effect relationship between set-asides and digital transformation, in this case proxied by the adoption of private networks.

If a country with set-asides has a high number of private networks, the set-aside policy might be seen as the cause, and the prevalence of private networks the effect. However, as shown in Figure 3, the observed relationship between the two is an outcome of multiple overlapping or bi-directional relationships between set-asides, private network adoption and other variables.

Figure 3
The relationship between set-aside policy, the adoption of private networks and example confounders



Source: GSMA Intelligence

How we performed robust statistical analysis

To provide robust evidence in the presence of overlapping and confounding relationships, we use statistical methods to separate the cause-and-effect relationship from other effects. The methods are discussed in detail in the Appendix. In brief, they take into account the following:

- independent growth trends in the adoption of set-asides and digitalisation, adjusting for their confounding effect
- observable confounders, adjusting for factors such as:
  - GDP per capita
  - 5G adoption among consumers
  - the general level of innovation in the economy
- unobservable confounders – we eliminate their influence by calculating adoption trends before and after the adoption of set-asides, and comparing these trends to those observed in countries with no set-aside spectrum.

The dataset used covers 51 countries between 2018 and 2022. The examined variables and data sources are summarised in Table 2. Certain limitations of the dataset should be acknowledged. As we use data on the number of private network customer launches, the dataset does not provide information on the actual number of private networks in every location. For example, a customer that has announced its first private network in 2020 may build additional networks in the future. As the only data available is for a customer launch in a particular country, the dataset will not reflect additional networks built by existing customers. No comprehensive international data currently exists on the number of individual private networks running in each country.

We also examine the impact of set-asides on the adoption of IoT technology by enterprises. Adoption of IoT is an important metric for digital transformation, with a greater number of enterprise connections indicating wider adoption of digital use cases. If set-asides provide an additional pathway to the adoption of wireless IoT devices (via private networks), this should be visible in the number of IoT connections. We examine whether the introduction of set-asides is associated with an increased number of connections, looking at enterprise IoT connections and low-power, wide-area (LPWA) connections, which are primarily used by enterprises. However, these counts can include connections supported by fixed or any type of wireless network (mobile, Wi-Fi and others).

Table 2

Datasets used to estimate the impact of set-asides on the digitalisation of enterprises

Outcome variables	Policy variables	Control variables
Number of announced private network customer launches *(GSA, 2023)*	Presence of set-aside spectrum *(GSMA Intelligence data collection, 2023)*	Logarithm of GDP per capita in USD constant prices *(IMF WEO projections, 2023)*
Number of enterprise IoT connections *(GSMA Intelligence estimates, 2023)*	Amount of MHz set aside *(GSMA Intelligence collection, 2023)*	Global Innovation Index *(WIPO, 2023)*
Number of LPWA connections *(GSMA Intelligence estimates, 2023)*		5G penetration *(GSMA Intelligence estimates, 2023)*

2.2 The impact of set-asides on the adoption of private networks

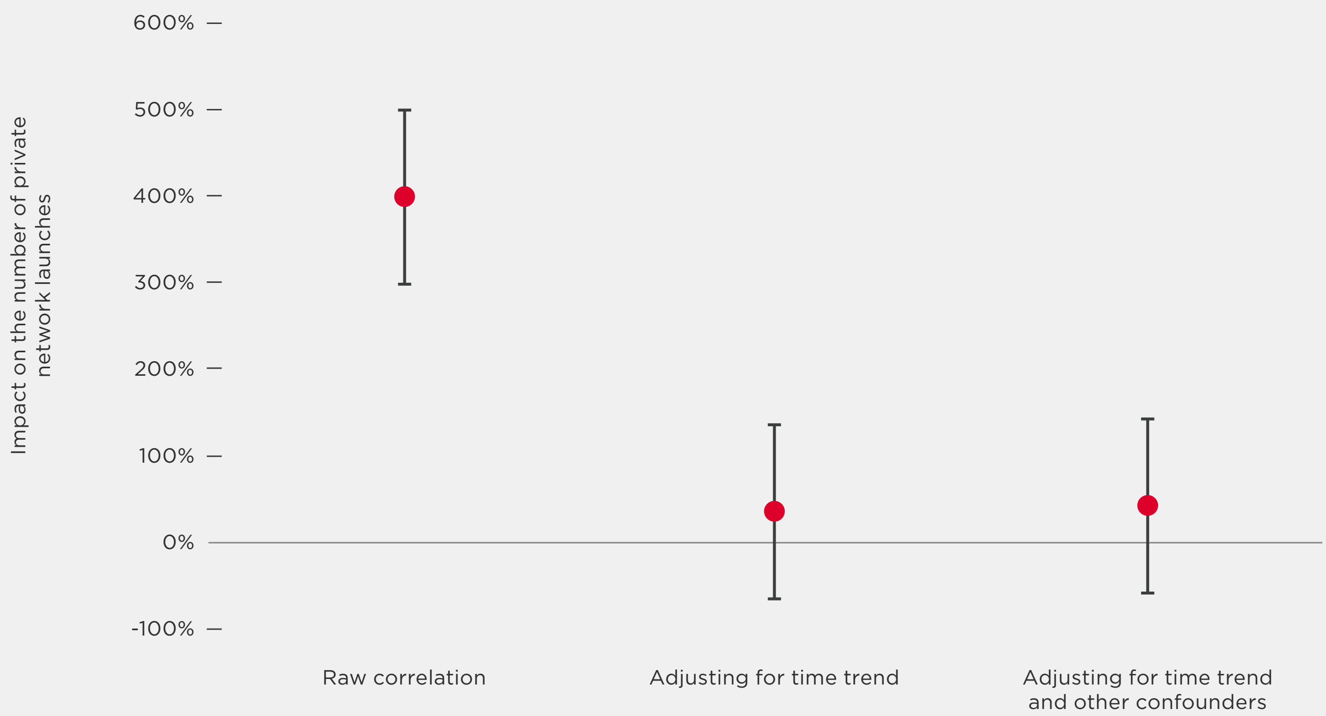
To understand the true impact of set-aside policies, we examine whether the presence of (any amount of) set-aside spectrum impacts the number of private network customer launches after adjusting for the presence of other effects.

Figure 4 presents a comparison of the results from three models. A raw correlation between the presence of set-asides and the number of private network customer launches could suggest that having set spectrum aside is associated with an increase in the number of private network customer launches by over 400%.

However, this can be quickly dismissed. After adjusting for the effect of time trends, the association between spectrum set-asides and the number of private network customer launches vanishes, with the result showing no statistical significance (indicated in Figure 4 by the vertical error bars). The same is observed after simultaneously adjusting for the effect of time trends and other confounders, showing no statistically significant effect of set-aside spectrum.

Considering all the relevant factors, there is no clear boost to private network adoption in countries that have set spectrum aside.

Figure 4
The impact of the presence of set-aside spectrum on private network customer launches



Source: GSMA Intelligence analysis

Why adjusting for time trends and confounders is essential

Time trends

Independent growth trends in the adoption of set-asides and private networks can lead to a spurious relationship observed between the two variables. This occurs because over the same period that 5G technology became available, there was a surge in the adoption of private networks by enterprises. At the same time, some countries sought to introduce set-asides, motivated by renewed interest in private networks due to new 5G capabilities.

These two growth trends independently affect both the adoption of private networks and the adoption of set-asides. However, they are causally unrelated to each other.

Other confounding variables

The adoption of set-asides and private networks can simultaneously be driven by external factors. For example, countries that have so far adopted set-asides have tended to be larger and more technologically advanced. These countries also tend to have a greater high-tech industrial base with the potential to adopt private networks. These would naturally see more private network launches regardless of the presence of set-aside spectrum.

Mere cross-country comparisons are therefore confounded by this and other observed and unobserved factors.

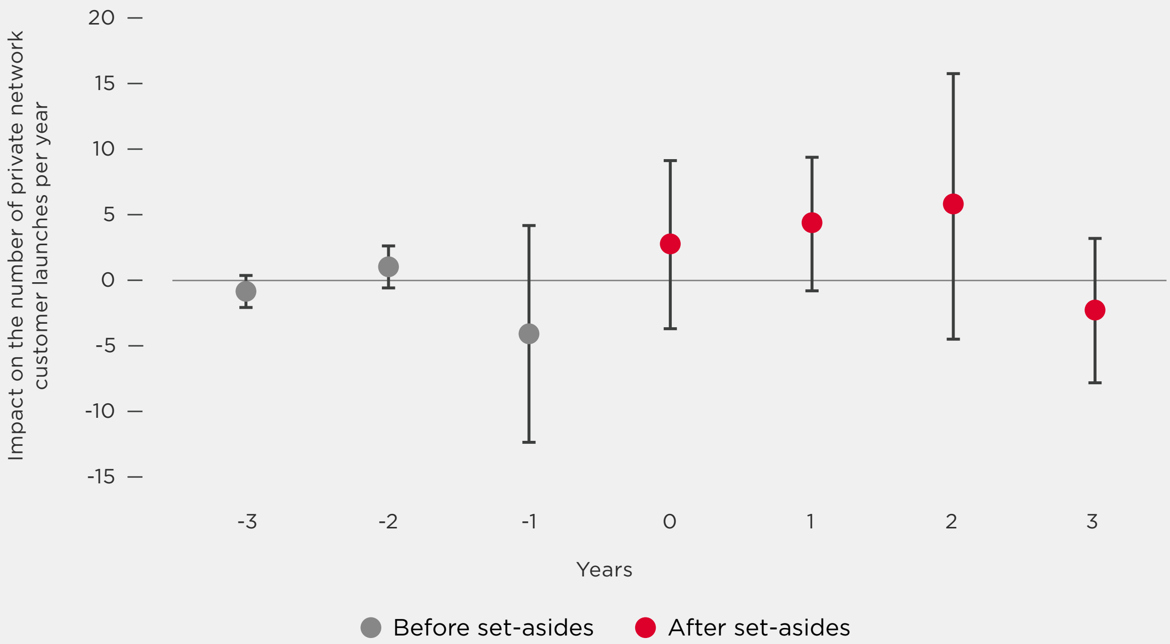
The results illustrate a key message in policy analysis: loose correlations do not necessarily mean a causal effect. It is important not to overinterpret correlations that are confounded by other effects. Instead, policy decisions should be based on evidence that partials out confounding effects, showing in this case that the impact of setting spectrum aside on private network adoption is uncertain.

This can be explained in various ways. In some cases, set-aside spectrum could make access to spectrum easier and more affordable for individual enterprises, playing a key role in the decision to adopt private networks. However, a lack of an overall effect means that set-asides are by no means necessary to enable the growth of private networks; enterprises in countries without dedicated set-aside spectrum have also been able to launch networks at a similar rate.

Lack of set-aside spectrum may not be a dealbreaker for most potential users, as spectrum can be accessed using alternative methods, such as shared bands or leasing from public network operators. Leveraging their expertise, public network operators frequently deliver end-to-end private network solutions to enterprises, with dedicated sub-leased spectrum as an integral part of the offering.

The impact of set-asides can also be examined over the time subsequent to any set-aside policy. Given that the policy change could take time to translate into an impact on private network launches, it could be hypothesised that the effect of policy could materialise gradually and with a delay. Figure 5 presents the timeline of impacts in a model adjusting for time trends and other confounders in the countries studied. It shows no statistically significant impact up to three years after setting spectrum aside. This further illustrates the uncertainty around the impact of set-asides.

Figure 5
The impact of setting aside spectrum on the number of private network launches

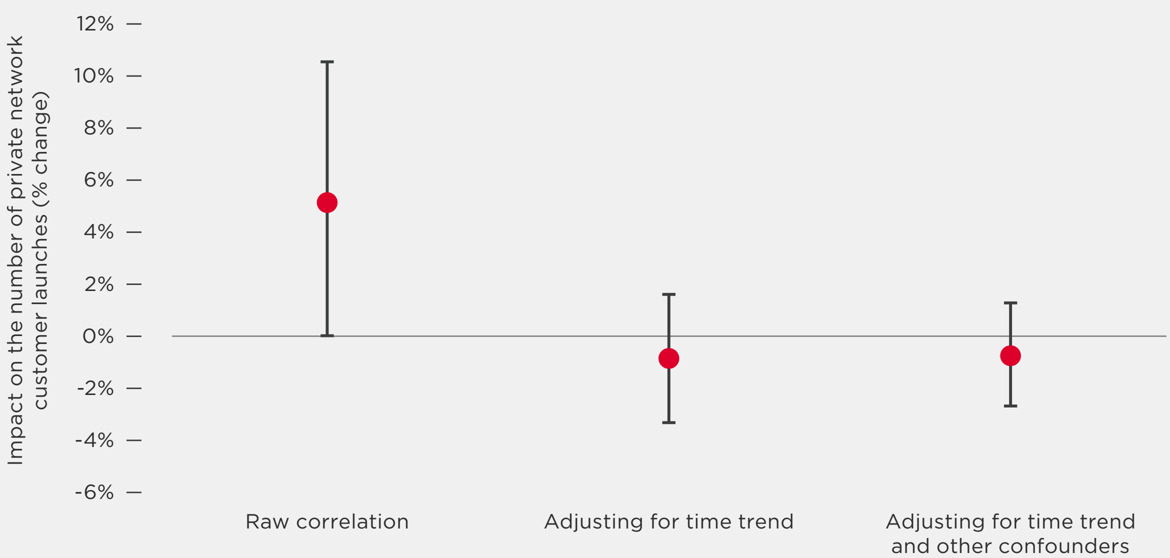


Source: GSMA Intelligence analysis

In addition, we can analyse the impact of the amount of set-aside spectrum on the number of private network customer launches (Figure 6). We examine this relationship to test whether, with more set-aside spectrum, enterprises face even lower barriers to setting up their private networks and can use them for the most demanding use cases requiring high-bandwidth connectivity.

A raw correlation shows 5% more private network customer launches for every 100 MHz of additional set-aside spectrum. However, when adjustments for time trends and other confounders are made, the association vanishes, showing no impact of the amount of set-aside spectrum. Regardless of how much spectrum is being set aside, it does not appear to be related to the rate at which enterprises adopt private networks.

Figure 6
The impact of setting aside an additional 100 MHz of spectrum on private network launches



Source: GSMA Intelligence analysis

2.3 The impact of set-asides on the adoption of IoT enterprise connectivity

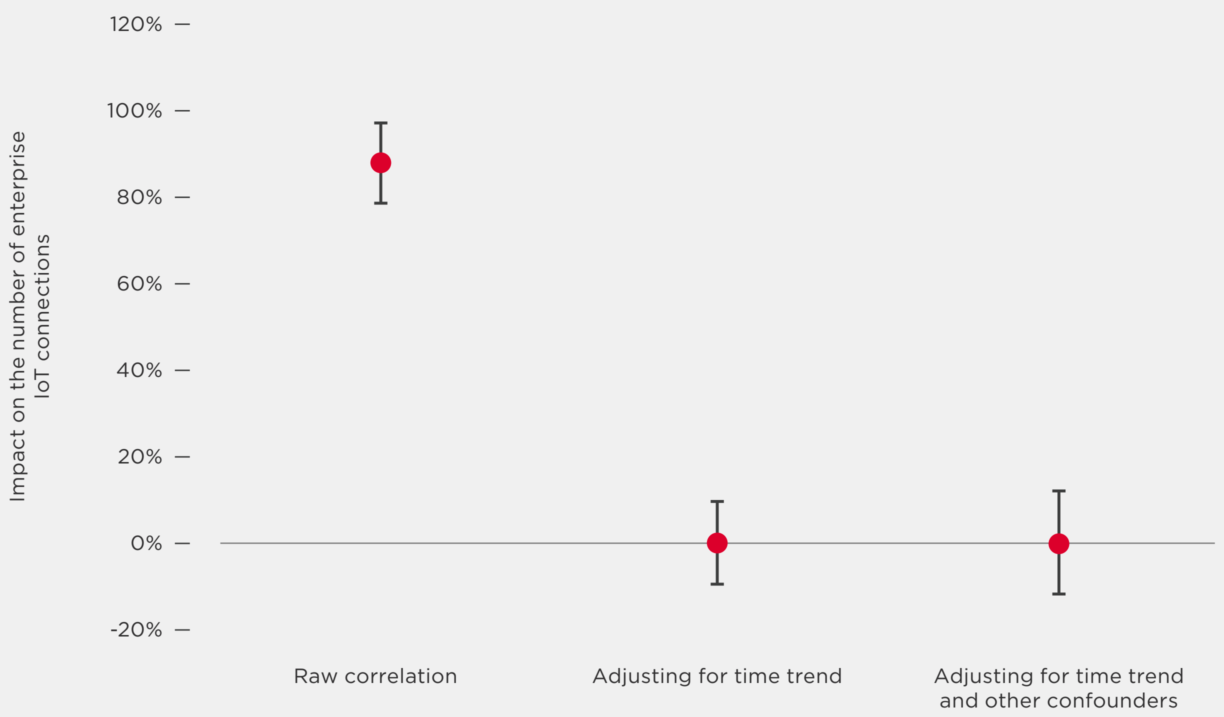
This study uses the number of IoT connections as an alternative proxy measure for the digitalisation of enterprises, with growth in the number of IoT connections indicative of adoption of advanced digital technologies. IoT connectivity adoption is a more proximate measure of the digitalisation of enterprises than private network adoption.

The impact of set-asides is examined according to two IoT adoption metrics:

- enterprise IoT connections – a GSMA Intelligence estimate of the total number of IoT connections operated by enterprises, supported by any type of connectivity, which may include fixed or different types of wireless connections (mobile, Wi-Fi)
- licensed LPWA connections[7] – typically serving enterprise applications in areas such as utilities, smart cities, logistics, agriculture and manufacturing.

Figure 7 compares the estimated effects of the presence of set-aside spectrum on the number of enterprise IoT connections. The relationship is affected most clearly by time trends. Concurrently to the growth in the number of IoT connections between 2014 and 2022, some countries were implementing set-aside policies. While the raw correlation could be misinterpreted as a sign of a strong positive effect of set-asides on the adoption of IoT connectivity, adjusting for the general time trend removes this association. The same is found for models with additional adjustments for other confounders, such as GDP per capita and the general level of innovation in the economy.

Figure 7
The impact of set-aside spectrum on the number of enterprise IoT connections

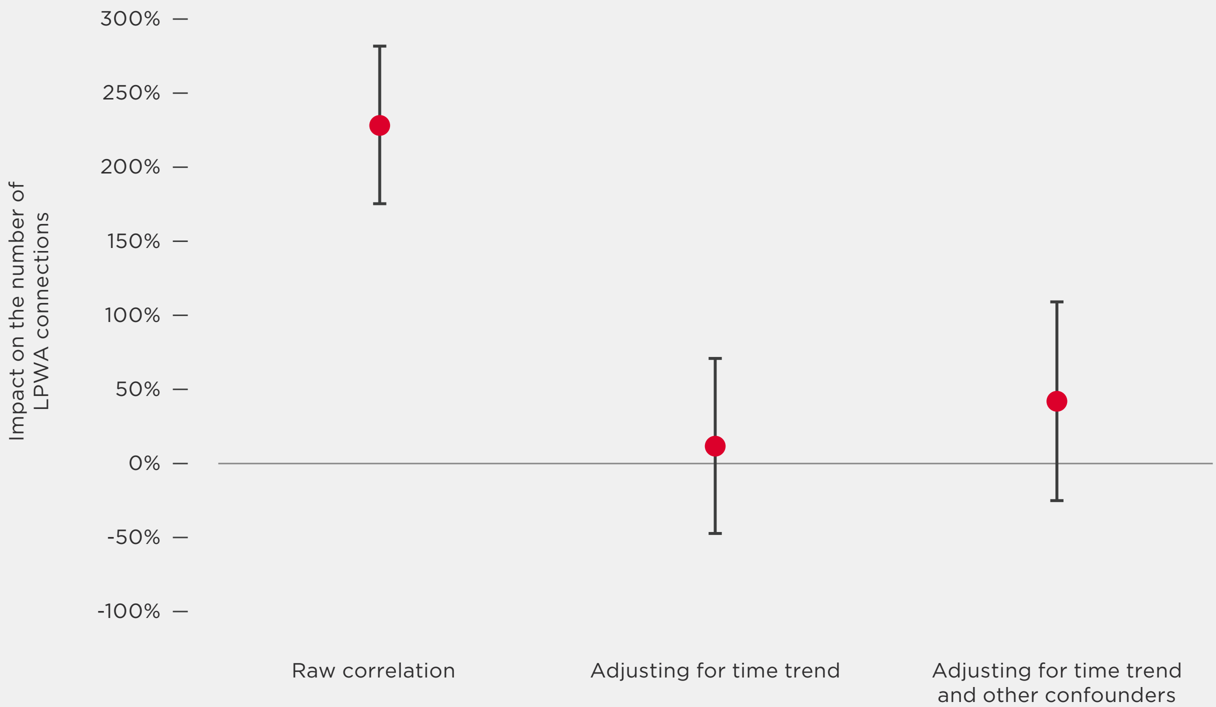


Source: GSMA Intelligence analysis

7. Mobile IoT (LPWA), GSMA

There is also a lack of causal link between set-asides and the number of LPWA IoT connections. As shown in Figure 8, a substantial positive association reduces to no impact once we control for time trends. Similarly, removing the confounding effect of factors such as economic growth and the general level of innovation results in an estimate of no statistically significant impact, shown by the 95% confidence interval bars indicating a range of possible positive and negative impact values.

Figure 8
The impact of set-aside spectrum on the number of LPWA connections



Source: GSMA Intelligence analysis

In summary, analysis of the number of IoT connections points to the same conclusions as for private network launches. The presence of set-asides does not appear to be an influential factor on the degree to which – or speed with which – enterprises adopt digital use cases, as proxied by adoption of IoT technologies. Enterprises are likely able to utilise various technologies and spectrum access options to support their IoT infrastructure. Among the many options available to enterprises to access IoT solutions, the availability of set-asides is likely not a deciding or sufficiently material factor influencing the level of adoption of IoT technologies.

The results present a cautionary warning on using simplistic analysis, as most of the observed relationship with set-asides can be explained by independent growth trends in the adoption of both set-asides and IoT technologies. These lead to spurious observed correlations, which vanish once the effect of confounders is adjusted for.

3. The impact of set-asides on public mobile networks

3.1 How set-asides reduce spectrum availability for public mobile networks

Any spectrum that is reserved for potential use by industries cannot be made available to other users. In most instances, this means less of it will be allocated to public mobile networks. Nearly all set-aside spectrum could have been dedicated to its internationally identified use for International Mobile Telecommunications (IMT) to provide enhanced service on public mobile networks. Examples include:

— the 2.3 GHz band set-aside in Finland, identified for IMT in the Radio Regulations (RR) for all regions and standardised as n40 5G NR band[8]

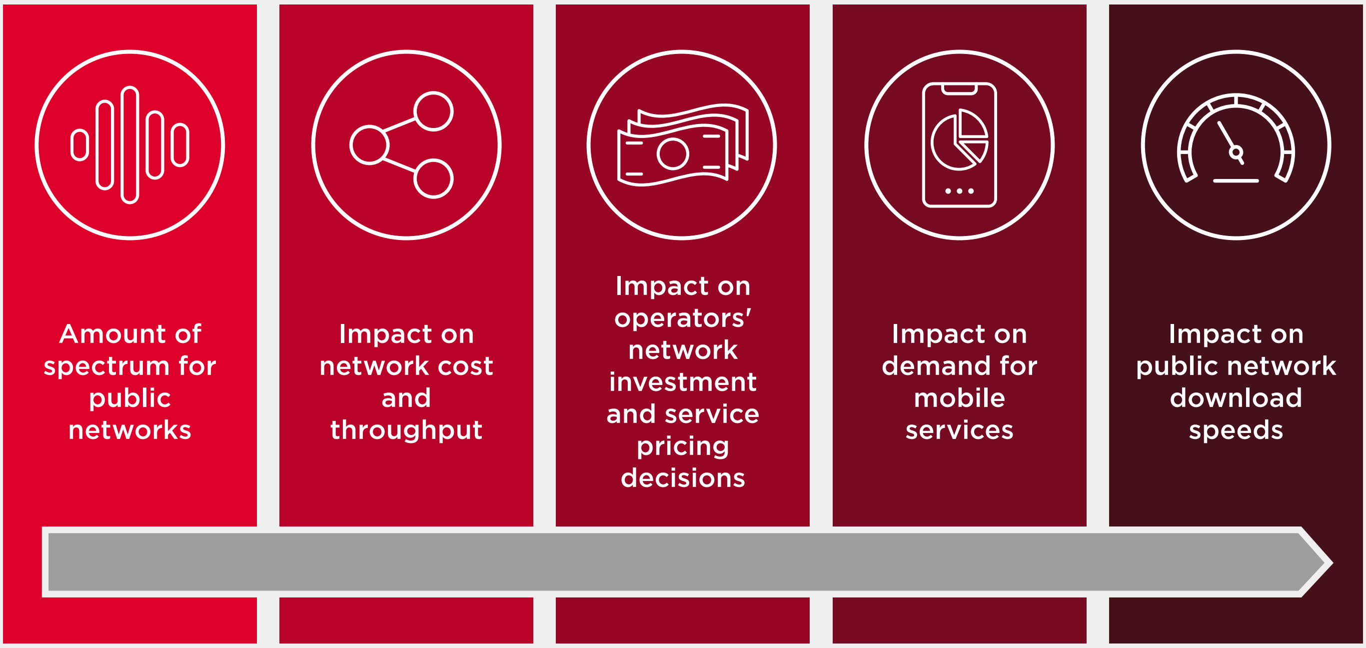
— the 2.5 GHz band set-aside in France, identified for IMT in the Radio Regulations (RR) for all regions and standardised as n41 5G NR band[9]

— the 3.8 GHz band set-aside in the UK, France and Germany, with its standardised use for IMT within the n77 5G NR band.[10]

Set-asides therefore present a trade-off, as they indirectly reduce the amount of spectrum available for public networks. Setting spectrum aside comes at an opportunity cost: the lost economic value that could have come from its alternative assignment to public networks, where it could enhance service quality and availability.

Spectrum is directly linked to network speed. The amount available to a mobile network determines maximum throughput per site (base station). With more spectrum available, networks can achieve higher throughput, or achieve the same throughput using fewer sites. The amount of available spectrum can therefore affect the cost of building and operating networks, their design, throughput and the user experience. This has a bearing on operators' investment and pricing decisions, impacting several other outcomes (see Figure 9). Of these, we focus on the impact of spectrum on download speeds, as this is a key determinant of the network quality experienced by consumers.

Figure 9
The impact of spectrum availability on public networks



Source: GSMA Intelligence

8. 5G spectrum for local industrial networks, Ericsson, 2023
9. "Arcep launches a public consultation on the terms and methods for allocating 2.6 GHz TDD band spectrum to support professional mobile radio networks' transition to 4G", Arcep, March 2018
10. "5G private licences spectrum in Europe", European 5G Observatory, April 2020

3.2 The impact on the speeds of public networks

To measure the link between the availability of spectrum and network speeds, we carried out a statistical examination of the dataset described in Table 3.

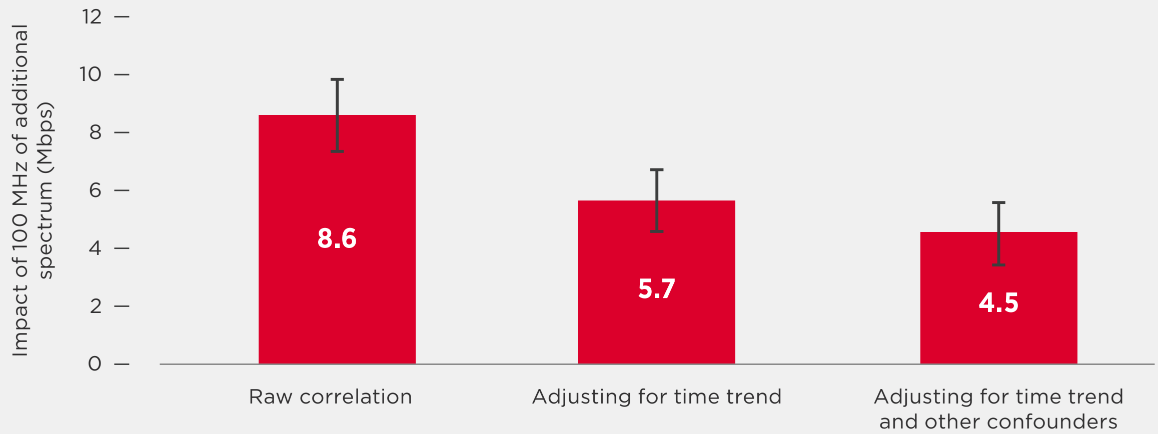
Table 3
Dataset used to estimate the impact of spectrum availability on the quality of public networks

Outcome variables	Policy variables	Control variables
Crowdsourced data on download speeds, 2014–2022 *(Ookla Speedtest Intelligence, 2023)*	Amount of IMT spectrum assigned to public mobile networks, 2014–2022 *(GSMA Intelligence Spectrum Navigator, 2023)*	Logarithm of GDP per capita in USD constant prices, 2014–2022 *(IMF WEO projections, 2023)* Global Innovation Index, 2014–2022 *(WIPO, 2023)*

Source: GSMA Intelligence

Figure 10 shows the estimated impact of 100 MHz of additional IMT spectrum on public mobile network download speeds. This estimate is based on a worldwide sample of average speeds in more than 140 countries between 2014 and 2022. While the raw correlation could suggest that 100 MHz of additional spectrum is associated with 8.6 Mbps greater download speeds, this is confounded by general growth trends and other effects, and should not be interpreted as a measure of a cause-and-effect relationship. Adjusting for the time trend and other confounders shows an estimate of 4.5 Mbps greater download speeds for an additional 100 MHz of spectrum. This is highly statistically significant, with a 95% confidence of the impact magnitude of 3.4–5.6 Mbps greater download speeds for 100 MHz of additional IMT spectrum. This set of results shows that the association between the amount of spectrum and performance of public networks remains strong even after controlling for confounders.

Figure 10
The impact of 100 MHz of additional IMT spectrum on public mobile network download speeds

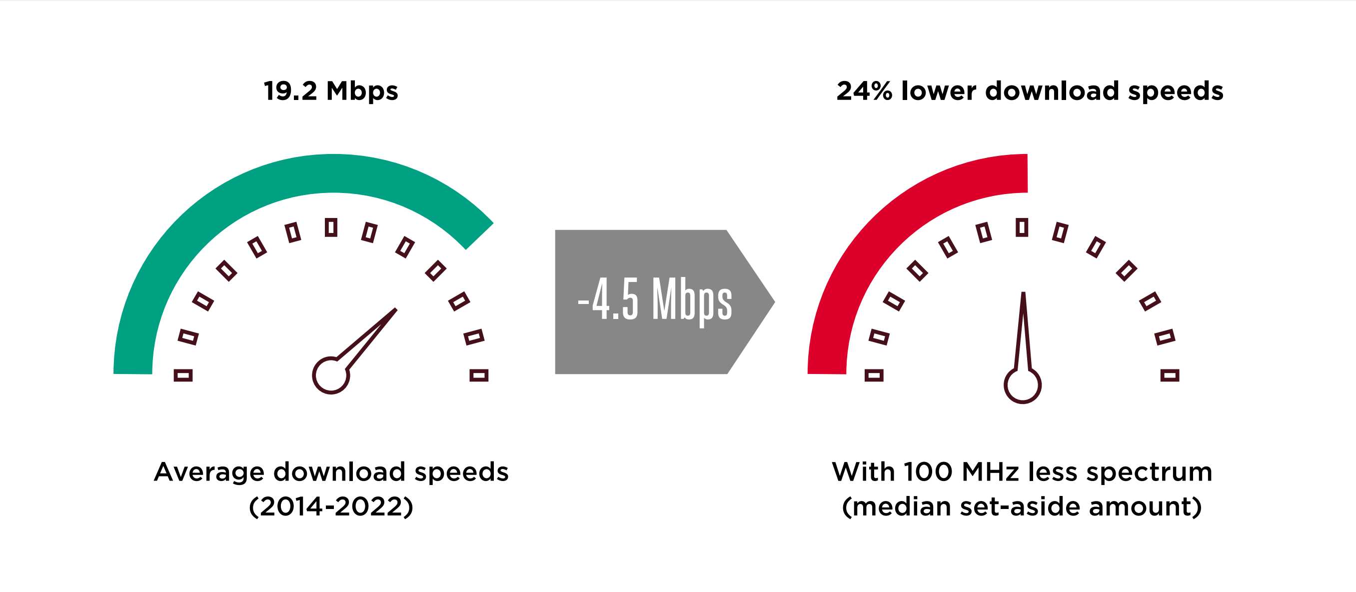


Source: GSMA Intelligence analysis

It is important to interpret this association in the context of average download speeds during the period examined (2014–2022). In the sample, the average global download speeds (weighted by the number of connections in each country) during the period stood at 19.2 Mbps (Figure 11). A difference of 4.5 Mbps translates into a 24% reduction in the download speeds experienced as a result of 100 MHz less spectrum for public mobile networks. This shows how material the unintended impact of set-aside spectrum could be, given that the median set-aside amount was precisely 100 MHz.

Figure 11

The impact of a 100 MHz difference in IMT spectrum on public network speeds



Source: GSMA Intelligence analysis

4. Conclusions

Networks need to keep up with the demands of cutting-edge services and their use cases

Accelerating adoption of industrial use cases is placing new demands on networks. Applications such as computer vision, sensor networks and generative-AI powered solutions require high-capacity, ultra-reliable and low-latency mass communication.

Among other infrastructure solutions that support the digitalisation of enterprises, 5G offers a strong proposition, with its built-in enterprise-focused features and services. As these features are widely supported by public 5G mobile networks, the digitalisation of enterprises will be mainly supported by such networks, with operators offering end-to-end solutions based on shared public infrastructure. However, some enterprises with unique connectivity needs may look to private networks to access these and other 5G features in a way that is tailored to their particular requirements.

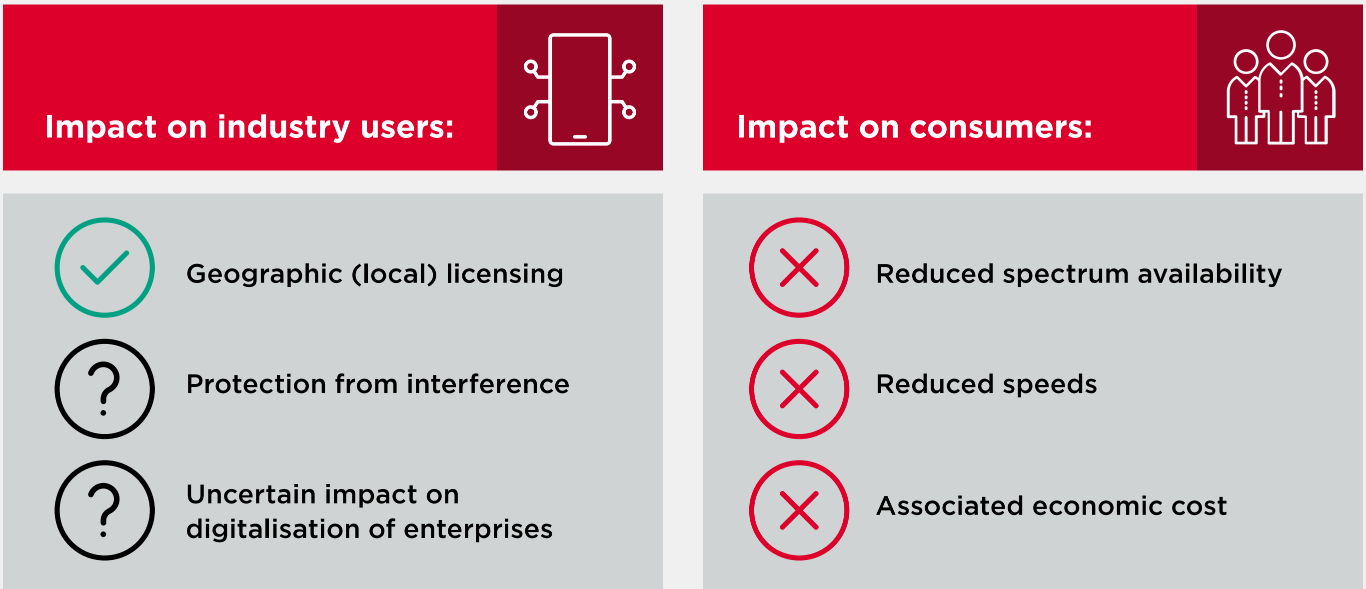
There are various options to make spectrum available as regulators look to foster network infrastructure development

Allocating spectrum to public mobile networks is a well-established practice. However, the frameworks of access to spectrum for private networks are still being explored. Among the options available, regulators can look to the following:

- spectrum sharing frameworks
- licence conditions mandating provision of required connectivity through public network operators
- spectrum set-asides to reserve use for potential local users.

Set-asides have a number of implications (see Figure 12). While providing access to enterprise users, they reduce the amount of spectrum available to public networks, with potential impacts on public network quality.

Figure 12
Set-asides as a spectrum licensing option



Source: GSMA Intelligence analysis

Analysis of the impact of set-asides shows no evidence of a positive effect on the digitalisation of enterprises

Data does not currently support the argument that setting aside spectrum boosts the adoption of private networks. Evidence from a sample of more than 50 countries during 2018–2022 shows no statistically significant impact on the number of private network customer launches. The apparent association between set-asides and private network adoption can be explained by other factors, with most of it arising from independent growth trends. The interest in set-asides and their adoption in recent years has coincided with the period when private network adoption accelerated – both likely driven by 5G technology becoming available. We find the same lack of evidence of a cause-and-effect relationship between set-asides and the adoption of IoT by enterprises.

The results indicate that having dedicated spectrum for enterprise use is not a necessary condition for the growth of private networks, and that other spectrum access frameworks can serve as a route to enable adoption. While in some instances set-asides may provide an easier or cheaper route to access spectrum, these factors do not prove to be critical for most enterprises choosing to rely on private networks. Examples of countries with no set-aside spectrum but a substantial number of private network customer launches include China and Poland.[11] Conversely, countries with reserved spectrum for enterprises also see a number of private network deployments supported by spectrum managed by or leased from public network operators as part of an end-to-end solution. This indicates the viability of using stipulations to provide private networks or lease spectrum, which can be attached to spectrum licences issued to public mobile network operators.

There is a clear opportunity cost of setting spectrum aside, as it could reduce public network speeds by 24%

Set-asides reduce the amount of spectrum available to public networks, where it could be used to provide enhanced bandwidth and reduce the cost of building and operating networks.

This study finds that a typical set-aside amount (100 MHz) could result in 24% lower download speeds for public networks. The result holds true after controlling for time trends and other confounders, indicating a strong relationship between the amount of spectrum and performance of public networks, and confirming the findings of previous studies.

The opportunity cost, measured in terms of impact on public network speeds, is an undesirable consequence of set-asides. It should not be overlooked, given the widely accepted objective of regulators and administrations to maximise the economic value of spectrum as a public resource.

Policymakers should avoid basing conclusions on correlations and one-sided analyses, overlooking the indirect and unintended consequences of set-asides

This robust statistical analysis contrasts with the claims founded on simple correlations and cross country comparisons.[12,13] In most cases, simple correlations are not informative as measures of the impact of a policy. Not adjusting for the confounding effects of time trends and other factors leads to an overstatement of the significance and magnitude of the link between policy on set-asides and the adoption of digital technologies.

The results of this study serve as a reminder that correlation does not mean causation. Policymakers should remain aware of the strengths and weaknesses of each evidence type.

11. GSMA 5G Transformation Hub: Helping Public and Private 5G to Work Together and The Impact of Spectrum Set-Asides on 5G - India
12. Market study: private wireless networks using 4G or 5G, Australia Communications and Media Authority, 2023
13. Private Mobile Networks: Member report February 2024, GSA, 2024

Careful consideration is needed of the options to make spectrum available for enterprises

Given the uncertain benefits but clear cost of set-asides, policymakers should carefully consider all the alternative options for making spectrum available to enterprises.

Unlike auction-based assignments for public networks, set-asides are not subject to a test of the economic efficiency of spectrum. The spectrum in set-aside bands is frequently assigned on a non-competitive basis to select types of player, often excluding public network operators.

Offering set-aside spectrum at reduced or no cost leads to distorted incentives in the market for digital solutions and infrastructure. Pricing spectrum differently depending on whether it is used by public or private networks can impact the relative cost of each solution type. As the cost saving is passed on to prospective users, the use of private networks is effectively subsidised. This can put public mobile network-based solutions at a disadvantage where they otherwise would have been the optimal choice. This can lead to economic inefficiency.

Alternative frameworks, such as using stipulations to provide private networks in operator licence conditions, preserve the market incentive to put spectrum to the use that generates the most economic value. Network operators that compete for access to spectrum on an equal footing have an incentive to put it to the use that generates the most economic value, whether this means leasing spectrum to enterprises, offering private network services, or using spectrum to enhance public network services and features (network slicing).

This evaluation sheds light on the early stages of adoption of private networks and set-asides. Similarly, new evidence will start to emerge on the performance of spectrum sharing frameworks and licence conditions. Policymakers should monitor this evidence and, where possible, take the initiative to collect data and perform evaluations of spectrum access frameworks.

5. Appendix

5.1 Empirical strategy

5.1.1 Approach to hypothesis testing

In this study, we empirically examine a set of hypotheses measuring the impact of spectrum set-asides on the digitalisation of enterprises and the quality of public mobile networks.

Impact on digitalisation of enterprises

1. The impact of set-asides on the number of private network customer launches
2. The impact of the amount of set-aside spectrum on the number of private network customer launches
3. The impact of set-asides on the number of enterprise IoT connections
4. The impact of set-asides on the number of licensed low-power, wide-area (LPWA) connections

Impact on the quality of public mobile networks

5. The impact of the amount of spectrum available to public mobile network operators on the average weighted download speeds experienced by consumers

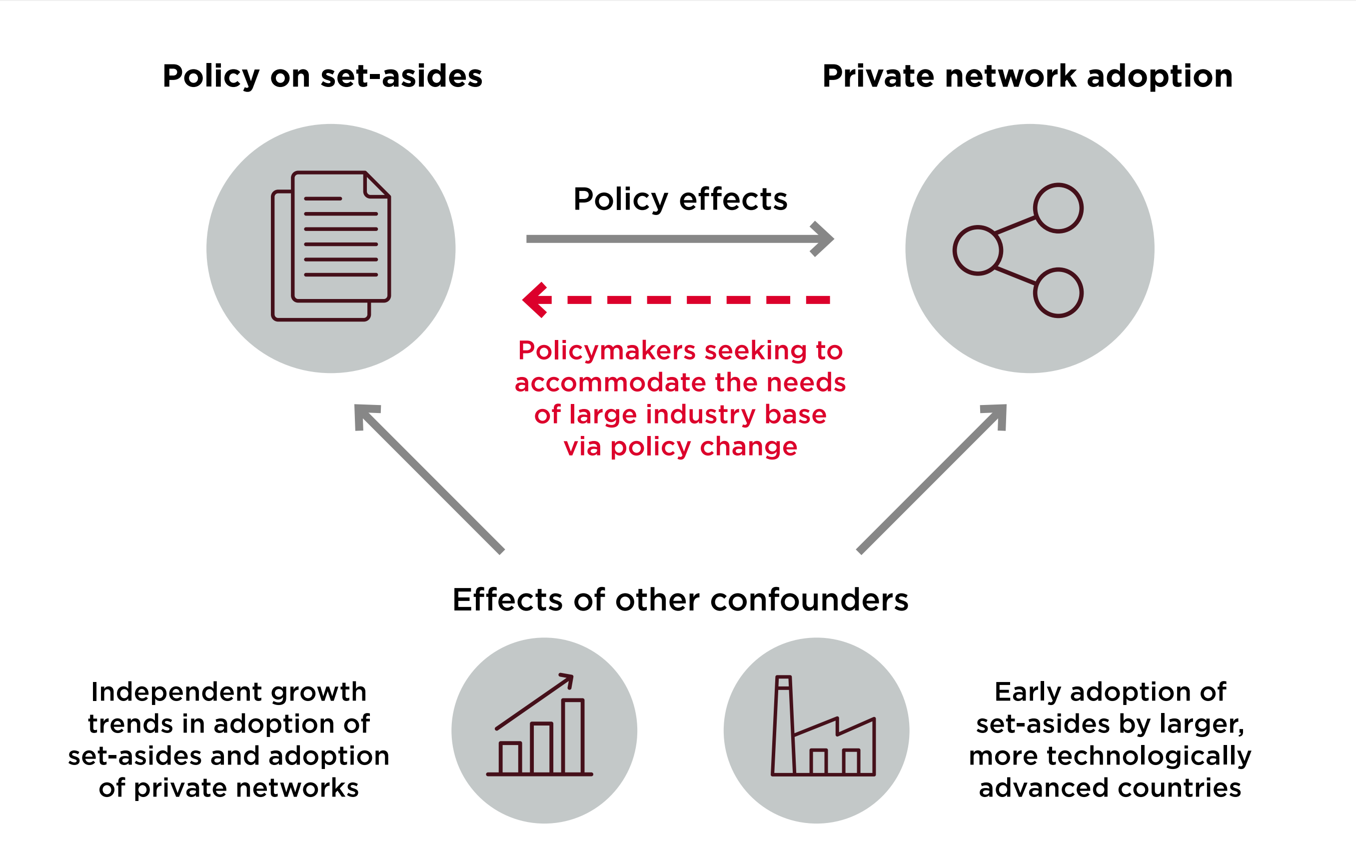
Using collated datasets, we examine the support for these hypotheses through statistical testing. This means we statistically estimate equations corresponding to each hypothesis, with each equation being a representation of the relationships between the examined variables.

How to measure the cause-and-effect relationship between set-asides and digitalisation

Measuring the impact of policy entails identifying the cause-and-effect relationship between policies and outcomes. However, as shown in the example for set-asides and private networks in Figure A1, the observed relationship between the two variables is an outcome of multiple overlapping or bi-directional relationships:

- The actual effect of the policy on the outcome – for example, an impact of set-asides on the adoption of private networks.
- The reverse causal effect of the outcome on the policy. For example, the emergence of private networks might generate interest among policymakers in how they could be promoted further.
- The effect of time trends. This occurs because at the same time as 5G technology became available, there was a surge in the adoption of private networks by enterprises. Concurrently, policymakers in multiple countries introduced set-asides, motivated by the new enterprise-oriented 5G capabilities. This 5G-driven trend independently affected both the adoption of private networks and the adoption of set-asides.
- The effect of other confounders. For example, countries that adopted set-asides tended to be larger and more technologically advanced. These countries also tend to have a greater high-tech industrial base with the potential to adopt private networks. These would see more private network launches regardless of the presence of set-aside spectrum. Mere cross-country comparisons are confounded by this and other effects.

Figure A1
The relationship between set-aside policy, adoption of private networks and example confounders



Source: GSMA Intelligence analysis

This set of simultaneous relationships can lead to endogeneity bias if relying on inappropriate statistical techniques. This means, for example, that the magnitude of the estimated parameter in pooled or cross-sectional models is a net result of all factors, including those omitted – rather than a measure of the policy effect alone.

We therefore rely on appropriate statistical methods and a set of control variables to remove the influence of confounding effects. For each tested hypothesis, we use the tailored statistical approaches described in the following sections.

5.1.2 The impact of set-asides on the number of private network customer launches

To estimate the impact of set-aside spectrum, we rely on a Poisson fixed-effects estimator.[14] This type of estimator is appropriate as our dependent (outcome) variable is a count of private network customer launches per year. Poisson fixed-effects estimators are also robust to issues such as excess zeros or overdispersion in the count data distribution, with the latter present in the distribution of private network launches in our sample. Relying on Poisson fixed-effects estimators therefore alleviates any concerns about the appropriateness of model choice against other types of count data models (negative binomial, zero-inflated negative binomial).[15]

Fixed-effects models are also advantageous in this context as they can exploit variation in policy and outcomes within each country, rather than making inferences based on cross-country comparisons. They eliminate unobservable confounding factors that are specific to each country and could otherwise bias the estimate.

Due to the Poisson fixed-effects estimator being a generalised linear model predicting the logarithm of the outcome variable as a linear projection of explanatory variables, the estimator calculates the policy effect as an incidence rate ratio (IRR). The IRR can be interpreted as the percentage difference in the number of private network customer launches per year as a result of introducing (any amount of) set-aside spectrum.

As specified in Table A1, the estimated model includes controls for potential confounders that varied over time, including the level of GDP per capita, level of innovation in the economy and the 5G penetration rate among consumers – a proxy for the degree of adoption of consumer mobile technologies. The model includes year indicator variables used to control for simultaneous but independent trends in the adoption of private networks and set-asides.

This approach tackles the main potential sources of bias in the identified policy impact parameter: those arising from time trends, and observable and unobservable confounders. However, some bias may still remain in the estimated parameter due to the hypothetical reverse direction relationship, as high local demand for private networks can trigger the decision of the regulator to introduce set-asides. Such an endogenous relationship can plausibly result in an upward bias in the estimated impact of set-asides on the adoption of private networks. However, as discussed in the context of the results, the existence of a positive bias in the identified parameter does not modify the conclusion of no positive impact of set-asides on the adoption of private networks.

Table A1

Specification of the model estimating the impact of the presence of set-aside spectrum on the number of private network customer launches

Outcome variables	Policy variables	Control variables
Number of private network customer launches per year *(GSA, 2023)*	Indicator of presence of set-aside spectrum *(GSMA Intelligence, 2023)*	Logarithm of GDP per capita *(IMF WEO projections, 2023)* Global Innovation Index *(WIPO, 2023)* 5G penetration *(GSMA Intelligence estimates, 2023)* Year

Source: GSMA Intelligence

14. Econometric Models for Count Data with an Application to the Patents-R & D Relationship, Econometrica, Volume 52, Issue 4, 1984
15. Distribution-free estimation of some nonlinear panel data models, Journal of Econometrics, Volume 90, Issue 1, 1999

As a robustness check, we estimate an additional model using the doubly robust difference-in-differences (DRDID) technique.[16] The DRDID estimator is frequently used in event studies and aims to discern the impact of policy change (treatment effect) by comparing the trends between groups that experience policy change and those that do not. In contrast to two-way fixed-effects estimators, the DRDID technique can be a more robust estimator for more complicated designs – for example, when different groups experience policy change in different periods, resulting in a staggered treatment.[17] The DRDID estimator also remains unbiased if the treatment effect of policy change varies between groups and over time (heterogeneous treatment effect). The DRDID estimator conditions the treated and untreated group selection on observables, to reduce the influence of differential pre-treatment trends in outcomes.[18]

5.1.3 The impact of the amount of spectrum set-aside on the number of private network customer launches

Similarly to the impact of the presence of set-aside spectrum, we rely on the Poisson fixed-effects estimator for the impact of the amount of set-aside spectrum on the number of private network customer launches each year.

The model estimates the effect of policy as an IRR, which is interpreted as a percentage change in the number of private network customer launches for an additional 100 MHz of set-aside spectrum. The model therefore imposes an implicit assumption on the shape of the relationship between the amount of set-aside spectrum and the number of customer launches each year. However, the results are not sensitive to the choice of this assumption, as similar estimates were obtained using an alternative functional form (logged amount of spectrum, results not presented here).

Table A2
Specification of the model estimating the impact of the amount of set-aside spectrum on the number of private network customer launches

Outcome variables	Policy variables	Control variables
Number of announced private network customer launches *(GSA, 2023)*	Amount of MHz set aside (100s) *(GSMA Intelligence collection, 2023)*	Logarithm of GDP per capita *(IMF WEO projections, 2023)* Global Innovation Index *(WIPO, 2023)* 5G penetration *(GSMA Intelligence estimates, 2023)* Year

Source: GSMA Intelligence

16. Doubly robust difference-in-differences estimators, Journal of Econometrics Volume 219, Issue 1, 2020
17. Two-way fixed effects and differences-in-differences with heterogeneous treatment effects: a survey, The Econometrics Journal, Volume 26, Issue 3, 2023
18. Now trending: Coping with non-parallel trends in difference-in-differences analysis, Statistical Methods in Medical Research, Volume 28, Issue 12, 2018

5.1.4 The impact of set-asides on the number of enterprise IoT connections and number of LPWA connections

To estimate the impact on the number of enterprise IoT connections and number of LPWA connections, we rely on two-way fixed-effects models. This type of estimator is suitable for dealing with continuous outcome and policy variables, such as the number of enterprise IoT connections per country.

Similarly to the previously discussed Poisson models, the two-way fixed-effects model exploits variation in policy and outcome variables within each country. This alleviates concerns about many sources of the omitted variable bias linked to unobservable characteristics of each country, which can simultaneously affect the propensity to adopt set-asides and IoT technologies. The estimated two-way fixed-effects model controls for these country-specific unobservables.

Nevertheless, we control for some factors that evolved over the period studied for each country, such as the level of GDP per capita, the general level of innovation in the economy, and 5G penetration as a general measure of the speed of adoption of 5G. In addition, we include year indicator variables as controls for time trends in both the outcome and the policy variables.

We use a semi-logarithmic functional form for the estimated equation, meaning that we transform the outcome variable by taking a natural logarithm of it. Such a transformation imposes an assumption on the form of the estimated relationship, which should be interpreted as the percentage change in the number of connections as a result of the introduction of spectrum set-asides. This form of relationship can be advantageous, as in the presence of vast differences in country sizes, we expect the policy change to have an effect proportional to the size of the country, rather than in terms of the absolute number of IoT connections.

Table A3
Specification of the model estimating the impact of the amount of set-aside spectrum on the number of enterprise IoT connections and number of LPWA IoT connections

Outcome variables	Policy variables	Control variables
Logarithm of the number of enterprise IoT connections *(GSMA Intelligence estimates, 2023)* Logarithm of the number of LPWA connections *(GSMA Intelligence estimates, 2023)*	Indicator of presence of set-aside spectrum *(GSMA Intelligence collection, 2023)*	Logarithm of GDP per capita *(IMF WEO projections, 2023)* Global Innovation Index *(WIPO, 2023)* 5G penetration *(GSMA Intelligence estimates, 2023)* Year

Source: GSMA Intelligence

5.1.5 The impact of the amount of spectrum available to public mobile networks on download speeds experienced by consumers

Spectrum set-asides present a trade-off, as they reduce the amount of spectrum available to public mobile networks. To estimate the relationship between the amount of spectrum available to public mobile network operators and network speeds, we rely on two-way fixed-effects models. In addition to controls for time trends, the specification includes GDP per capita and the Innovation Index (Table A4).

However, in contrast to specifications estimating the impact of set-asides, the model examined here does not include a control for 5G penetration. Controlling for 5G penetration would mean estimating the impact of the amount of IMT spectrum on speeds when holding 5G penetration constant. As the degree of 5G penetration is also affected by the amount of IMT spectrum available to network operators, the parameter of interest in this case should identify the total impact, as a product of:

- availability of additional spectrum enhancing network throughput
- availability of spectrum accelerating the rollout of 5G network and its enhanced throughput.

We estimate the equation in levels form, meaning that the estimated parameter measures the change in download speeds (Mbps) for a 100 MHz increase in the amount of IMT spectrum assigned to public mobile networks.

Table A4
Specification of the model estimating the impact of the amount of spectrum assigned to public mobile networks on network speeds

Outcome variables	Policy variables	Control variables
Crowdsourced data on download speeds in Mbps, 2014–2022 *(Ookla Speedtest Intelligence, 2023)*	Amount of IMT spectrum assigned to public mobile networks in 100s of MHz, 2014–2022 *(GSMA Spectrum Navigator, 2023)*	Logarithm of GDP per capita in USD, 2014–2022 *(IMF WEO projections, 2023)* Global Innovation Index, 2014–2022 *(WIPO, 2023)* Year

Source: GSMA Intelligence

5.2 Dataset

Limitations of existing datasets

As the aim of this study is to assess the degree to which spectrum set-asides impact the digitalisation of enterprises, we examined the suitability of different metrics for digitalisation. While some data is already being collected by national statistics offices, it is of limited geographic coverage or collected with limited frequency. For example, Eurostat's 'ICT usage in enterprises' data collections provide data on the use of ICT systems by enterprises, and even a composite digital intensity measure. However, the collections cover only EU member states and are conducted every two years, with limited availability of indicators before 2019 (making 2019 and 2021 the only available collections at the time of writing). The geographical and time coverage of these is therefore too restrictive to support statistical analysis.

Indicators from international economic cooperation bodies, such as the World Bank and OECD, are limited. The World Bank does not list specific enterprise digitalisation measures. Some indicators have been compiled by the OECD, but these concern only a few selected countries and are one-off collections, making them unsuitable for statistical trend analysis.[19] We therefore focus on other available measures that serve as proxies of digitalisation and can be linked through theory of change to set-aside policy.

Data sources

As a first measure of the digitalisation of enterprises, we rely on data on the number of private network customer launches. This was sourced from the Global Mobile Suppliers Association (GSA) GAMBoD database.[20] While other sources of data on private networks exist from commercial suppliers, GSA GAMBoD data claims the greatest number of private network customers, suggesting more exhaustive coverage. The data was collected from the vendors of 5G network equipment who jointly account for the vast majority of market share.

The unit of analysis is a private network customer launch (by, for example, an enterprise or public sector body) in a given country. In some instances, the country of launch was suppressed in the GAMBoD database due to non-disclosure requirements. These observations were dropped from our dataset, as the customer launch cannot be allocated to a particular country. The dataset also excludes testbeds and smaller deployments (worth less than €100,000). In total, our database consists of data on private network customer launches from almost 40 countries, as we focus analysis on countries with at least two private network customers added during 2018–2022. We supplemented the data with desk-based research to collect public domain announcements of customer launches in 12 remaining EU countries, providing comprehensive coverage of the bloc.

As a second measure of enterprise digitalisation, we use the number of enterprise-operated IoT connections. IoT connections serve as a proxy of the adoption of various digital technologies, as each IoT connection represents connected devices, which could include remote sensors, connected vehicles or production line devices, for example. We rely on two different counts of enterprise-operated connections:

- Enterprise IoT connection estimates, developed by GSMA Intelligence. These estimates are based on the number of connections reported by ISPs and other predictors. The connections include all types, whether on mobile or fixed networks.

- LPWA connection estimates, developed by GSMA Intelligence. Typically, LPWA connections are used in industrial applications such as smart grids, sensor networks and smart meters. The figures are for LPWA connections using licensed spectrum. The estimates are based on reporting by ISPs and other predictors.

Data on the presence of set-aside spectrum comes from GSMA Intelligence, based on desk research conducted between June and August 2023. The scope of surveyed countries included those in the GAMBoD database and an additional 12 EU countries to ensure comprehensive coverage of the bloc. Information was obtained from national regulators' websites and other public domain sources. In some instances, the spectrum access framework may have characteristics of both set-asides and a sharing framework. An example is

19. Measuring the Digital Transformation, OECD, 2019
20. GAMBoD, Global Mobile Suppliers Association

the CBRS framework in the US, which in principle can be considered a sharing framework due to localised incumbent presence which prevents use by industries. However, the framework is designed to provide access to enterprises by reserving its use, away from public IMT networks. We therefore consider it a set-aside for the purposes of conducted empirical research.

Data on average download speeds experienced by consumers is obtained from the Ookla Speedtest Intelligence database.[21] Download speed measures are crowdsourced using Ookla's mobile app and aggregated. To obtain weighted download speeds, the mean download speeds for each mobile network generation are weighted using the number of connections for each network generation in a given country. The number of connections for each network generation is sourced from the GSMA Intelligence database.

Data on the amount of spectrum assigned to mobile operators was obtained from the GSMA Intelligence Spectrum Navigator database, supplemented with data and validation by national regulators. The total amount of spectrum (in MHz) for each country and year has been obtained as the sum of MHz of active licences in that year. The total includes all IMT bands used by mobile radio access networks but excludes high (above 6 GHz) and mmWave bands, as these were not widely deployed during the period of analysis.

As well as the key policy and outcome variables, we source data on control variables. We use IMF data on GDP per capita, measured in US dollars, adjusted for purchasing power parity (PPP) and inflation, sourced from the World Economic Outlook publication (April 2023 version).[22] The Global Innovation Index (GII) is compiled by the World Intellectual Property Organization.[23] In our models, it serves as a proxy for the general level of innovation of the economy. The GII is an index measure of innovation of each country, measuring pillars such as infrastructure, human capital, quality of institutions and others. Data on 5G penetration among consumers is a GSMA Intelligence estimate, measured as the percentage of the total population with a 5G connection. This is calculated as a ratio using the number of connections reported by operators and population data.

The sources of data used in estimation are listed in Table A5, while the descriptive statistics for the estimation dataset are shown in Table A6.

Table A5

Data sources used in building the estimation dataset

Variable	Period	Source
Number of private network customer launches announced	2018–2022	Global Mobile Suppliers Association GAMBoD, July 2023 version
Presence of set-aside spectrum	2016–2022	GSMA Intelligence, based on desk research, 2023 collection
Amount of MHz set aside	2018–2022	GSMA Intelligence, based on desk research, 2023 collection
Crowdsourced data on download speeds in Mbps	2014–2022	Ookla Speedtest Intelligence, 2023
Number of enterprise IoT connections	2014–2022	GSMA Intelligence estimates, 2023
Number of licensed LPWA IoT connections	2016–2022	GSMA Intelligence estimates, 2023
Amount of IMT spectrum assigned to public mobile networks	2014–2022	GSMA Intelligence Spectrum Navigator database and other sources, 2023
GDP per capita in USD constant prices	2014–2022	IMF World Economic Outlook, 2023
Global Innovation Index	2014–2022	World Intellectual Property Organization, 2023

Source: GSMA Intelligence

21. Speedtest Intelligence, Ookla, 2023
22. World Economic Outlook, International Monetary Fund, 2023
23. The Global innovation Index 2023, World Intellectual Property Organization, 2023

Table A6
Descriptive statistics for the estimation dataset

Variable	Unit	Obser-vations	Mean	Std. dev.	Min	Max
Private network customer launches	Units	306	1.89	5.26	–	47
Amount of spectrum set aside	MHz	306	122	574	–	5,300
5G consumer penetration	% of population	306	3.8	8.5	–	54.4
Number of enterprise IoT connections	Units	459	9.3m	34m	0.2m	3.5bn
Number of licensed LPWA IoT connections	Units	245	3.7m	26m	164	306m
Weighted download speed	Mbps	1,575	16.7	19.9	0.3	267.2
Spectrum assigned to public mobile networks	MHz, IMT bands below 6 GHz	1,575	393	266	–	1,321
GDP per capita	USD PPP, constant prices	1,564	21,283	22,136	387	143,982
Global Innovation Index	Index	1,175	35.7	12.4	11.6	68.4

Note: The number of observations is based on the maximum number of observations available in the estimated equations. The number of observations used in estimation of individual equations may vary depending on combinations of missing data.
Source: GSMA Intelligence analysis

5.3 The impact of set-asides on the digitalisation of enterprises – detailed results

5.3.1 The impact of set-asides on the adoption of private networks

Table A7 presents the results of the Poisson fixed-effects estimator. The coefficients are reported as IRRs. Values above 1 indicate an increase in the number of private network launches (with, for example, 1.1 indicating a 10% greater number of launches). Conversely, values below 1 indicate a negative association. The estimated probability values are presented in parentheses and derived from robust standard error estimates.

Due to the multitude of potential endogenous relationships, the coefficients on control variables, such as the GDP per capita, should not be interpreted as parameters identifying causal effects.

Table A7

The impact of the presence of set-aside spectrum on private network customer launches

	Raw correlation	Controlling for time trends	Controlling for time trends and other confounders
Set-aside present: all bands	5.015 ***	1.338	1.391
	(0.00)	(0.38)	(0.34)
GDP per capita			0.148
			(0.51)
5G penetration			0.991
			(0.24)
Global Innovation Index			1.058
			(0.60)
Year		Controls included	Controls included
Number of observations	264	264	254

Note: Coefficients reported as IRR. Impact of the presence of a set-aside in all spectrum bands. Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

Table A8 presents the estimated impacts of set-asides based on the DRDID estimator. The impacts are presented as differences in private network customer launches between never treated or not yet treated countries (meaning not having set-aside spectrum) and treated countries (already with spectrum set aside). These differences are estimated for each pre- and post-treatment year.

Table A8
DRDID estimates of the impact of the presence of set-aside spectrum on private network customer launches, 2018–2022 sample

		Co-efficient	Std. err.	Z score	P>|z|	95% confidence interval	
Average treatment effect of set-asides		3.72	2.90	1.28	0.20	-1.97	9.41
Effect size pre-treatment **Periods to set-aside:**	**4**	(omitted)					
	3	-0.80	0.60	-1.33	0.18	-1.98	0.38
	2	1.03	0.84	1.22	0.22	-0.62	2.68
	1	-4.04	4.24	-0.95	0.34	-12.34	4.27
Effect size post-treatment **Periods with set-aside:**	**0**	2.77	3.26	0.85	0.40	-3.63	9.17
	1	4.34	2.61	1.66	0.10	-0.78	9.47
	2	5.69	5.17	1.10	0.27	-4.43	15.82
	3	-2.22	2.79	-0.80	0.43	-7.69	3.24

Note: Coefficients reported as the number of additional private network customer launches. Impact of the presence of a set-aside in all spectrum bands. Probability values calculated using robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

Table A9 presents additional estimates examining the impact of the amount of set-aside spectrum on the number of private network customer launches. The impacts, based on the Poisson fixed effects regression model, are presented as an IRR. A value of 1.05 for the raw correlation model with no controls should be interpreted as a 5% increase in the number of private network customer launches for an additional 100 MHz of set-aside spectrum. Parameter values of less than 1 indicate a negative impact point estimate, though these do not reach statistical confidence level in models controlling for time trends and other confounders.

Table A9

The impact of the amount of set-aside spectrum on private network customer launches

	Raw correlation	Controlling for time trends	Controlling for time trends and other confounders
100 MHz set-aside	1.051 **	0.991	0.992
	(0.05)	(0.46)	(0.46)
GDP per capita			0.118
			(0.50)
5G penetration			0.993
			(0.36)
Global Innovation Index			1.056
			(0.61)
Year		Controls included	Controls included
Number of observations	264	264	254

Note: Coefficients reported as IRR. Impact of the amount of set-aside in all spectrum bands. Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

5.3.2 The impact of set-asides on the adoption of IoT connectivity by enterprises

Table A10 shows the estimated impact of set-asides on the number of enterprise IoT connections. The estimated coefficient should be interpreted as a percentage change in the number of IoT connections as a result of the presence of set-aside spectrum. Thus the coefficient of 0.004 in the model controlling for time trends and other confounders indicates a 0.4% point estimate of the impact, which is not statistically significant (probability values are given in parentheses).

Table A10

The impact of the presence of set-aside spectrum on the number of enterprise IoT connections

	Raw correlation	Controlling for time trends	Controlling for time trends and other confounders
Set-aside present: all bands	0.878 ***	0.002	0.004
	(0.00)	(0.97)	(0.94)
GDP per capita			-0.029
			(0.90)
5G penetration			0.000
			(0.99)
Global Innovation Index			-0.003
			(0.72)
Year		Controls included	Controls included
Number of observations	459	459	445
F statistic	367.18	274.33	259.02

Note: Dependent variable: logarithm of enterprise IoT connections. 2014–2022 sample (unbalanced panel). Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

Table A11 shows the results of the estimated effect of set-aside spectrum on the number of LPWA IoT connections. In the models controlling for time trends and other confounders, the estimated coefficients are not statistically significant.

Table A11
The impact of presence of set-aside spectrum on the number of LPWA IoT connections

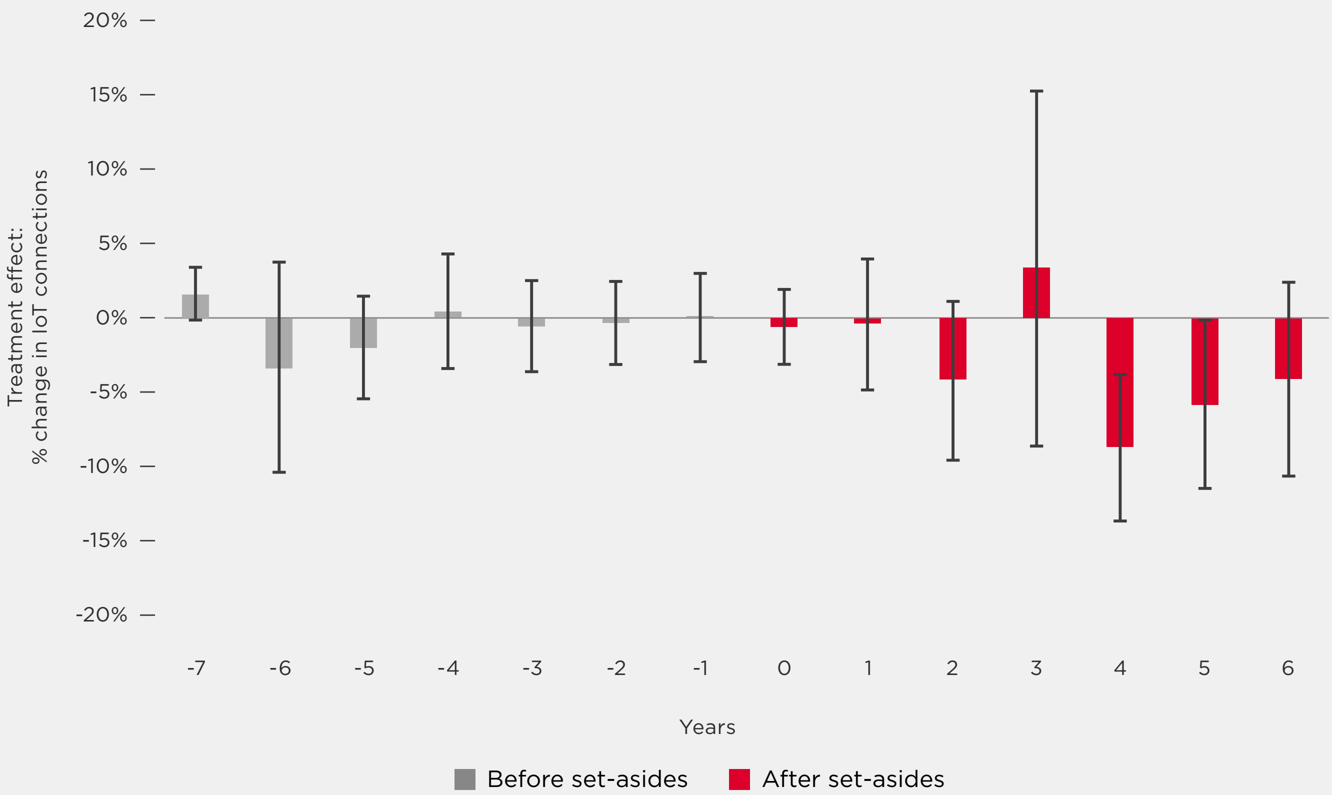
	Raw correlation	Controlling for time trends	Controlling for time trends and other confounders
Set-aside present: all bands	2.286 ***	0.105	0.408
	(0.00)	(0.72)	(0.23)
GDP per capita			-0.028
			(0.99)
5G penetration			-0.036 ***
			(0.00)
Global Innovation Index			0.042
			(0.41)
Year		Controls included	Controls included
Number of observations	245	245	239
F statistic	76.08	114.20	99.26

Note: Dependent variable: logarithm of enterprise LPWA IoT connections. 2016–2022 sample (unbalanced panel). Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

Figures A2 and A3 provide plots of the DRDID-estimated impacts of set-asides on the number of enterprise IoT connections and LPWA IoT connections, respectively. These show the estimated treatment effect in individual years from the introduction of set-asides, with the estimates typically scattered around positive and negative values and not reaching statistical significance.

Figure A2
The impact of spectrum set-asides on the number of enterprise IoT connections estimated using the DRDID technique



Note: Dependent variable: logarithm of enterprise IoT connections. 2014–2022 sample (unbalanced panel). 95% confidence intervals calculated using robust standard errors.
Source: GSMA Intelligence analysis

Table A12
DRDID estimates of the impact of the presence of set-aside spectrum on the number of enterprise IoT connections

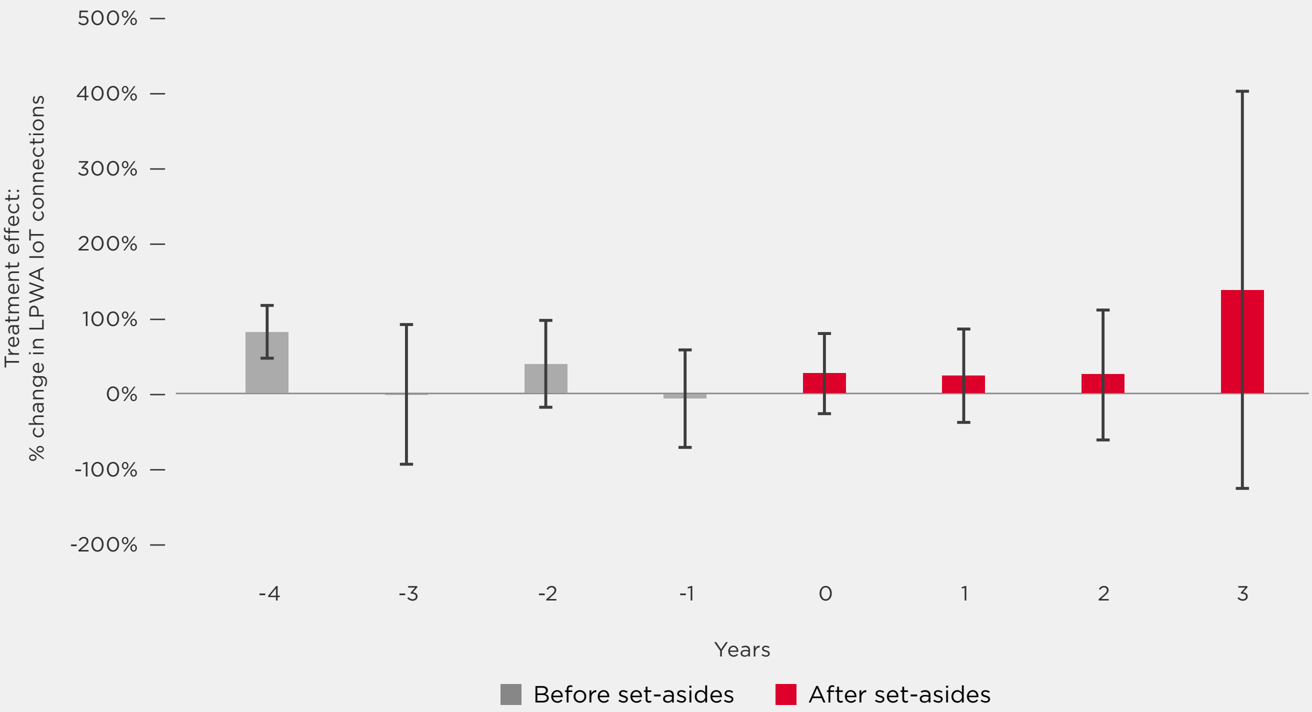
		Co-efficient	Std. err.	Z score	P>|z|	95% confidence interval	
Average treatment effect of set-asides		-0.01	0.02	-0.67	0.51	-0.06	0.03
Effect size pre-treatment **Periods to set-aside:**	**7**	0.02	0.01	1.81	0.07	0.00	0.03
	6	-0.03	0.04	-0.91	0.36	-0.11	0.04
	5	-0.02	0.02	-1.12	0.26	-0.06	0.02
	4	0.00	0.02	0.23	0.82	-0.03	0.04
	3	-0.01	0.02	-0.36	0.72	-0.04	0.03
	2	0.00	0.01	-0.24	0.81	-0.03	0.02
	1	0.00	0.02	0.02	0.99	-0.03	0.03
Effect size post-treatment **Periods with set-aside:**	**0**	-0.01	0.01	-0.51	0.61	-0.03	0.02
	1	0.00	0.02	-0.19	0.85	-0.05	0.04
	2	-0.04	0.03	-1.52	0.13	-0.10	0.01
	3	0.03	0.06	0.55	0.58	-0.09	0.16
	4	-0.09 ***	0.03	-3.46	0.00	-0.14	-0.04
	5	-0.06 **	0.03	-2.04	0.04	-0.12	0.00
	6	-0.04	0.03	-1.22	0.22	-0.11	0.02

Note: Dependent variable: logarithm of enterprise IoT connections. 2014–2022 sample (unbalanced panel). Robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

Figure A3

The impact of spectrum set-asides on the number of LPWA IoT connections estimated using the DRDID technique



Note: Dependent variable: logarithm of LPWA connections. 2016–2022 sample (unbalanced panel). Probability values in parentheses. 95% confidence intervals calculated using robust standard errors.

Source: GSMA Intelligence analysis

Table A13
DRDID estimates of the impact of the presence of set-aside spectrum on the number of LPWA connections, 2016–2022 sample

		Co-efficient	Std. err.	Z score	P>|z|	95% confidence interval	
Average treatment effect of set-asides		0.32	0.39	0.81	0.42	-0.45	1.09
Effect size pre-treatment **Periods to set-aside:**	**4**	0.82	0.18	4.49	0.00	0.46	1.18
	3	-0.02	0.48	-0.04	0.96	-0.97	0.92
	2	0.39	0.30	1.30	0.20	-0.20	0.99
	1	-0.08	0.33	-0.23	0.82	-0.73	0.58
Effect size post-treatment **Periods with set-aside:**	**0**	0.26	0.28	0.94	0.35	-0.28	0.81
	1	0.24	0.32	0.73	0.46	-0.40	0.87
	2	0.24	0.45	0.54	0.59	-0.64	1.12
	3	1.38	1.36	1.02	0.31	-1.28	4.04

Note: Dependent variable: logarithm of LPWA connections. 2016–2022 sample (unbalanced panel). Robust standard errors. Asterisks attached to the coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

5.4 The impact of spectrum amount on public mobile networks – detailed results

5.4.1 The impact on download speeds of public networks

Table A14 shows detailed results on the relationship between the amount of IMT spectrum (in MHz) and download speeds (in Mbps) of public mobile networks. The estimates are obtained using the two-way fixed effects estimator, and the models are enhanced with controls for GDP per capita and level of innovation in the economy.

As with previously discussed results, coefficients on control variables should not be interpreted as measures of causal effects due to the possible influence of endogeneity and the omitted variable bias. Similarly, some bias may remain in the estimated effect of spectrum on download speeds due to the reverse causal effect and other unaccounted-for relationships.

Table A14
The impact of availability of spectrum on weighted download speeds (Mbps), 2014–2022 (unbalanced panel)

	Raw correlation	Controlling for time trends	Controlling for time trends and other confounders
100 MHz of IMT spectrum	8.578 ***	5.652 ***	4.528 ***
	(0.00)	(0.00)	(0.00)
Logarithm of GDP per capita			-9.484
			(0.25)
Global Innovation Index			1.491 **
			(0.01)
Year		Controls included	Controls included
Number of observations	1,575	1,575	1,174
F statistic	190.94	45.24	32.97

Note: Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence analysis

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