Bell Labs Consulting

NOKIA

Increasing fiber density

Imperative for 5G wireless-enabled fourth industrial revolution

White paper

Networks in transportation, health, energy and communications have been central to our economic and productivity growth. Rapid ongoing digitization will transform all these networks, making them smarter. In the coming years, the high-performance 5G wireless network will be central to this transformation. It will also help create a new smart digital manufacturing network for the next (fourth) industrial revolution. But, most emerging economies risk missing out because they are not ready for 5G. In previous wireless technology generations, access to a rich fiber network gave an operator a competitive edge. But now such access is indispensable for any operator serious about 5G. In the past, lack of fixed network infrastructure in emerging economies led to a wireless boom. With it came the economic benefits of telecom and broadband networks that were the purview of mature economies only. But now this fixed network deficiency is a hurdle for 5G deployment in these regions. Using analytical models, simulations and case studies, we show that left to market forces alone, the scale of investments in the fiber network needed for 5G readiness will not happen in many regions. We call this the “tragedy of missing commons.” This problem is best addressed by concerted government actions to help build a common deep fiber network infrastructure that all the communications market participants can share. They can then deliver competitive 5G connectivity and innovative value-added services.

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Introduction

Communication networks are indispensable to our lives today. It took decades of investments during much of the previous century for leading countries like the United States to build their nation-wide landline telephony network. As this network evolved to provide internet data services, the quest for improved performance led to the increasing deployment of fiber-optic cables replacing copper wires in much of the developed world. The initial displacement began in the network core and continued outward in the access network. While this move from the transmission of electric signals over copper wires to optical signals over fiber-optic cables was happening in the fixed network, the wireless network emerged as the default access technology because of its flexibility and reach. 5G, the next generation of wireless, promises not only fiber-like access speeds but also ultra-high reliability and extremely low latency.

In an increasingly digital society and economy, 5G, in combination with many cyber-physical technologies, will enable unprecedented levels of automation, accelerate productivity growth and spur the next industrial revolution. The previous generations of wireless networks helped emerging economies of the world close the digital gap with mature economies without investing extensively in the fixed network. Unfortunately, they now face the reckoning of the importance of fixed network investments. This is because fiber-like access speeds and other high-performance benefits of 5G networks accrue from an architecture that requires ultra-dense small cells shrinking the radio access to a short wireless drop, and high bandwidth connections from the radio access points to the core of the network. Unless there is deep fiber deployment, there cannot be ubiquitous 5G. Therefore, increasing “fiber density” (amount of fiber deployed per coverage area) is an important and urgent issue for operators and regulators to address. Some mature economies that are already fiber-rich, such as Japan and South Korea, have a clear advantage. Other than China, most emerging economies that do not have enough fiber deployment have made very little progress in this area. They should consider China’s aggressive investments a wake-up call, as they run the risk of falling behind on the next industrial revolution that will reshape the economies of nations.

Past: telephony networks and economic development

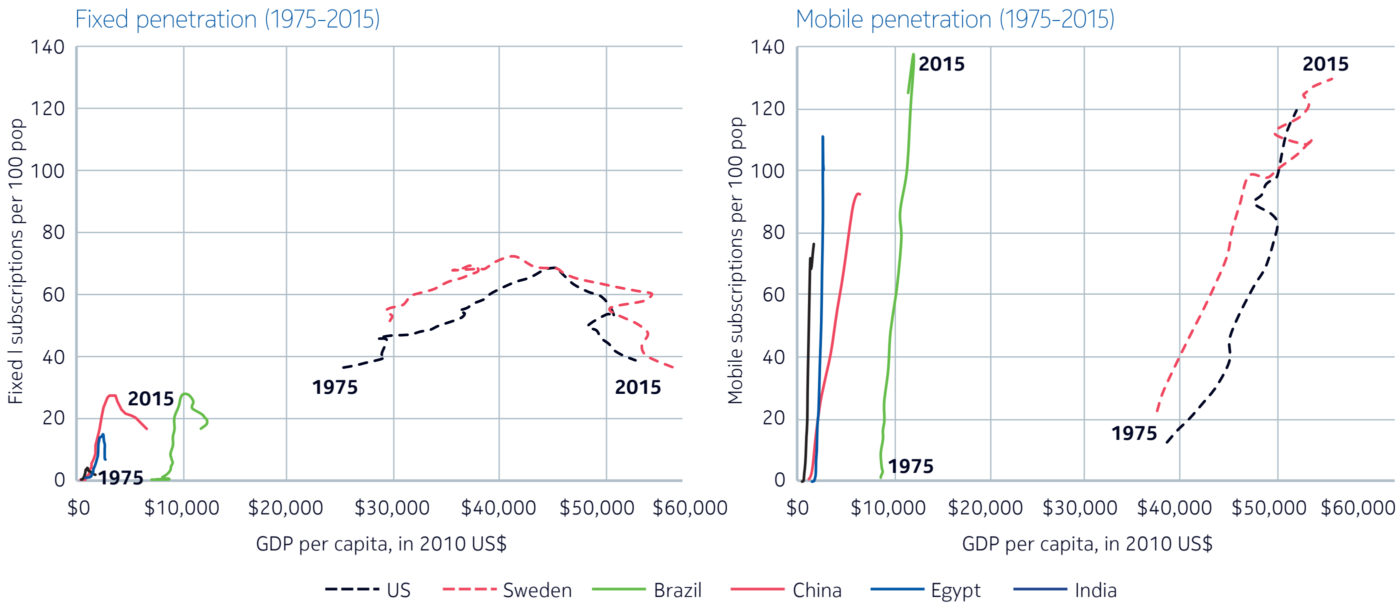
The invention of telephony toward the end of the 19th century changed how we communicated. People were able to communicate over long distances with ease, resulting in an improved information flow that benefited the overall society and economy. Communication networks, along with other key physical infrastructure networks such as transportation, gas and electricity, or water and sewage, contributed to the surge in productivity growth in mature economies like the United States through the 1970s.[1]

However, low-income countries were left behind because of their inadequate investments in these key infrastructure technologies.

In the 1990s the advent of cellular mobile telephony changed the communication networks landscape. Low- and middle-income countries constrained by a lack of capital for building large landline telephone networks could now connect billions of people through wireless service, closing the connectivity divide that existed between high-income and mid/low-income countries. Figure 1 below shows how connectivity networks evolved in representative high-, middle- and low-income countries in the last few decades.

1 Iraj Saniee, Sanjay Kamat, Subra Prakash and Marcus Weldon, “Will productivity growth return in the new digital era?,” Bell Labs Technical Journal, vol. 22 (2017).

Figure 1. Fixed and mobile penetration in select countries



Just as the high-income countries reaped the benefits of fixed connectivity, emerging economies gained similarly from the high penetration of mobile phones, which was achieved much faster. Studies[2] show that for each additional 10 phones per 100 people, on average the GDP per capita grew by 0.6 percentage points in emerging economies, and by 0.3 percentage points in mature economies.

The first two generations of wireless communications (1G and 2G) focused on improving the efficiency and quality of mobile telephony and migration from analog technologies to digital technologies. At the beginning of the 21st century, 3G (UMTS/WCDMA) arrived with a focus on providing mobile broadband data access at a minimum internet connectivity rate of 144Kbps. It is estimated that for a given level of total mobile penetration, a 10% increase in substitution from 2G to 3G increased GDP per capita growth by 0.15 percentage points.[3] 4G technologies followed this with one to two orders of magnitude in improvement, with peak data rates reaching up to 100 Mbps. Many applications using smartphones that we take for granted today, like video streaming and ride-hailing, were not viable before 4G. Countries began transitioning from 2G to 3G and then to 4G. With this transition, billions of people in emerging economies were connected to the internet and could reap similar economic benefits that people in mature economies got due to their robust fixed broadband infrastructure.

2 Leonard Waverman, Meloria Meschi and Melvyn Fuss, "The Impact of Telecoms on Economic Growth in Developing Countries," Vodafone Policy Paper Series 2 (2005): 10–24.

3 GSMA-Deloitte, What Is the Impact of Mobile telephony on Economic Growth? (London: The Creative Studio at Deloitte, November 2012).

Present: high-speed mobile data networks and fixed mobile convergence

Each generation of wireless technology specification enhances performance requirements, particularly the uplink and downlink speeds. This generates new demand for spectrum while enabling new applications on mobile devices, for example high-fidelity video streaming and high-resolution image uploading. This increases demand and eventually necessitates a change in network architecture. The network design criterion has shifted from optimizing for telephony experience (i.e., best voice quality with minimal call drops) to providing end users with the best mobile data experience (e.g., high downlink and uplink speeds and low latency).

Performance of a wireless network is primarily a function of transmission efficiencies over the air interface (the link between the end user device and the base station) and over the backhaul link (the connection between the baseband station and the core of the network). On the air interface side, factors that impact performance include spectral efficiency, which depends on the type of technology (3G, 4G LTE, LTE Advanced), spectrum availability, cell density, cell loading (number of concurrent active users), number of carriers, number of transmit and receive antennas, and use of advanced features such as carrier aggregation or massive MIMO with beamforming. On the backhaul side, the choice of technology used determines the supported capacity. There are three main backhaul choices for operators: (1) copper, (2) fiber and (3) microwave. Satellite may be an option in some restrictive cases. Table 1 below provides the pros and cons of the prevalent backhaul technologies.

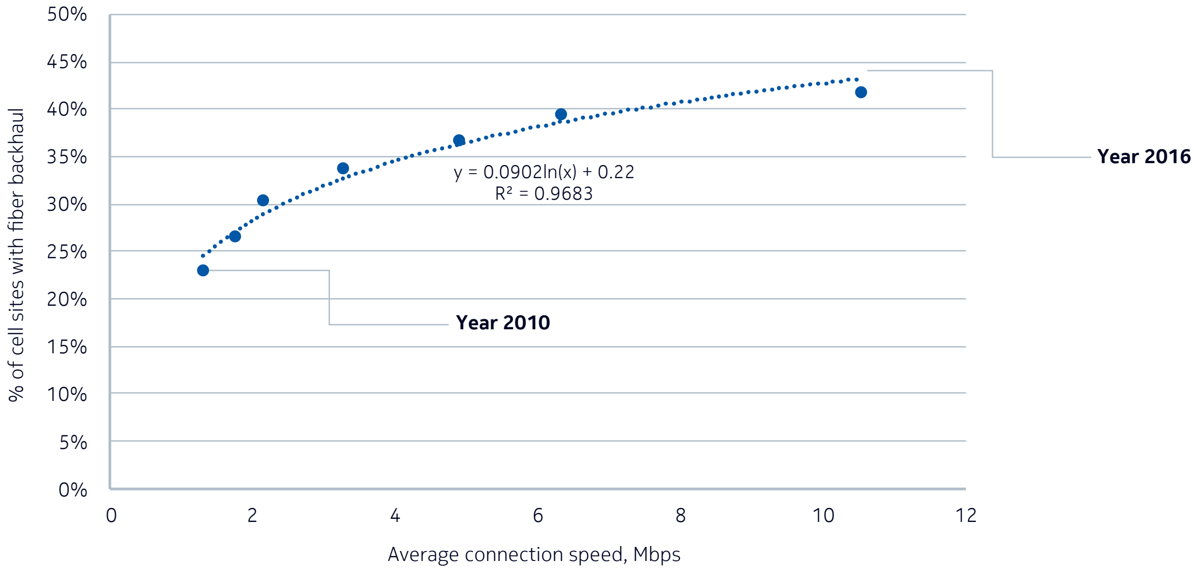
Table 1. Comparison of backhaul technologies

	Microwave (7–40 GHz)	Fiber-optic	Copper
Max speeds	1.5Gbps	1Tbps	150Mbps–1Gbps
Interference immunity	Medium	Very high	Very high
Range (km)	5–30++	<80	<15 (bonded) for 150Mbps <0.1 G.fast for 1Gbps
Time to deploy	Weeks	Months	Months
Cost (new build)	$	$$–$$$	$$–$$$

Copper has the lowest capacity, ranging from 1.5Mbps for T1 connections to up to 150Mbps download speeds when 12 pairs are bonded, and 1Gbps using G.fast over short copper loops. Fiber provides the maximum capacity and is considered future-proof technology. However, fiber is not currently deployed everywhere it is needed, and the time and cost of deploying new fiber can be significant. Microwave is the most common technology used today in most regions except North America. It is adequate for today’s throughput needs, has the benefit of ease of deployment, and costs less than fiber. Microwave technology is very popular in many countries where either access to existing fiber is limited or getting rights of way to deploy new fiber is challenging. However, the performance of microwave technologies is affected by environmental conditions and the line-of-sight requirement that makes microwave backhaul infeasible in many circumstances.

Fiber backhaul is considered future-proof, as it can accommodate future capacity needs and is the preferred choice if economically viable. Figure 2 shows that globally, as average wireless connection speeds increase, the percentage of cell sites with fiber backhaul has also been increasing.

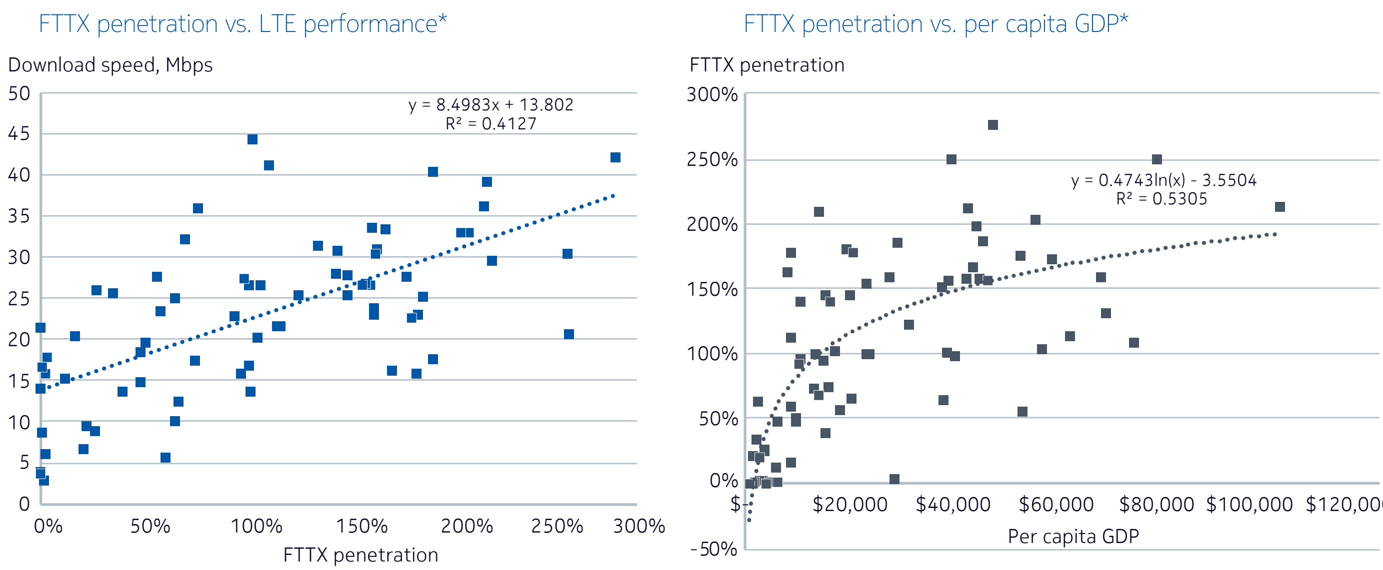
Figure 2. Fiber backhaul and wireless connection speeds



Source: Bell Labs Consulting analysis of data sourced from Akamai State of Internet Reports and IHS Mobile Backhaul Market Database 2Q18.

At the country level, as shown in Figure 3, we also see that there is a strong correlation between LTE speeds and fiber penetration. Countries with higher fiber penetration tend to have higher LTE speeds, and richer countries tend to have higher fiber penetration and higher LTE speeds.

Figure 3. LTE performance vs. FTTX penetration[4]



* LTE download speeds from OpenSignal, June 2018.

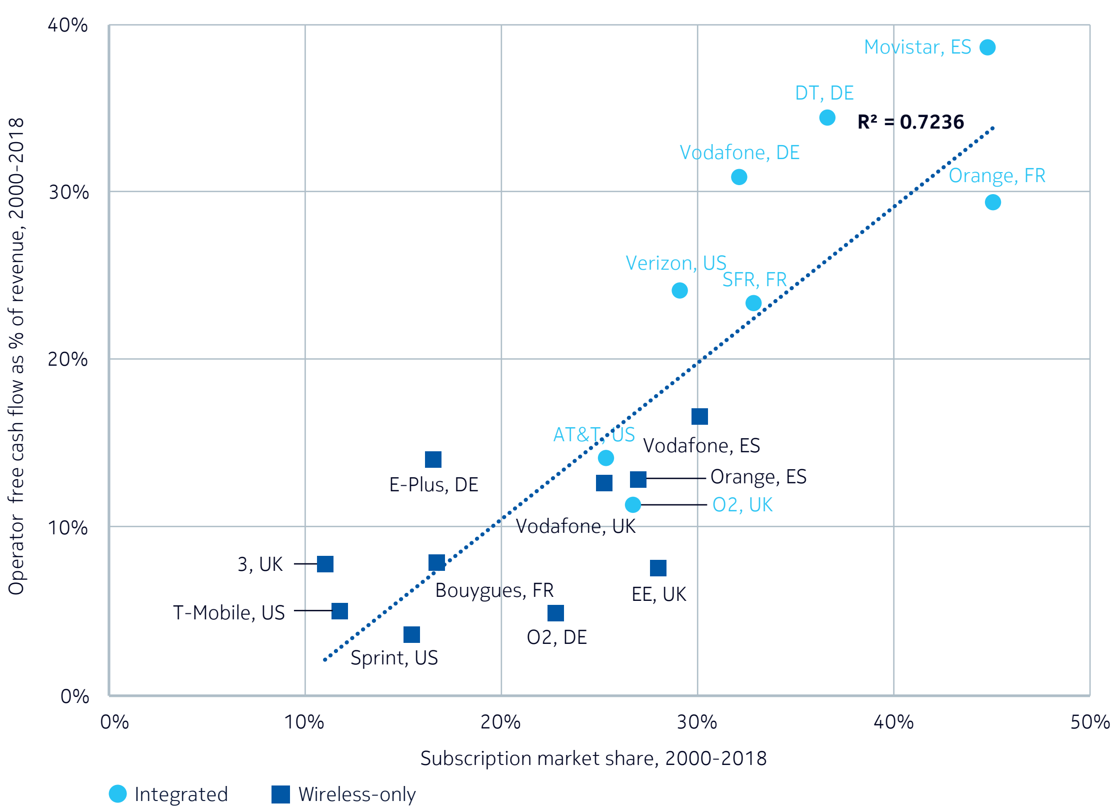
4 FTTX penetration = number of HH passed by FTTX, DOCSIS 3.1 fiber and VDSL/total number of HH. This is used as a measure of how deep fiber has been deployed in the country and can potentially be tapped for wireless backhaul. Since neighborhoods can access all three technologies deployed, the percentage of penetration can be greater than 100%.

Since LTE throughput is a function of many factors besides backhaul, this correlation does not necessarily imply causation. However, it is fair to argue that operators in richer countries have been able to make the appropriate investment in fiber deployment to ensure superior user experience.

The need for a robust fixed infrastructure for wireless operator success is also underscored by the fact that historically dominant and converged operators with both wireless and wireline services have performed better than wireless-only operators. Figure 4 shows our analysis of operators' financial performance from the year 2000 to the end of the first quarter of 2018 in four large markets – France, Germany, the US and the UK. We use free cash flow margin as a measure of economic strength, as it reflects the amount of organically generated funds available for discretionary investments in business growth or for paying dividends to shareholders. Converged operators demonstrate better returns than primarily wireless-only operators. One likely explanation is that they tend to have better overall performance and cost and are in a better position to provide attractive bundled offers to customers leveraging both their wireline and wireless assets.

Converged operators may start as converged or evolve to that position. The wireless industry in all areas is highly competitive and scale matters – higher market share is strongly correlated to higher operating free cash flow margins. Thus, dominant operators have more cash available to invest in their networks and improve quality to gain further market share or acquire smaller players to gain market share – further adding to profitability. This dynamic culminates when there are three to four providers left in the market and regulatory restrictions prevent further wireless consolidation. In such cases, wireless players tend to invest in or acquire operators with fixed assets (including cable multiple system operators (MSOs)). This has led to several wireless/wireline operator mergers, as shown in Table 2.

Figure 4. A comparison of historical financial performance (2000–2018) of integrated and wireless-only operators in France, Germany, the US and the UK



Source: Bell Labs Consulting analysis of GSMA Intelligence data.

Table 2. Convergence-driven mergers and acquisitions

Network operator	M&A target
Vodafone (Germany)	KDG (2014)
Vodafone (Spain)	Ono (2014)
China Mobile	TieTong (2015)
BT (UK)	EE (2016)
Orange (Spain)	Jazztel (2015)
Liberty Global (Belgium)	Base (2016)
Telecom Argentina	Cablevision (2018)
Vodafone (Germany, Eastern Europe)	Liberty Global (2018)
T-Mobile (Austria)	UPC (2018)

This discussion reinforces the significance of fixed network density for the financial success of wireless operators as wireless traffic grows, driving the need for high performance at low cost.

Future: 5G promise and dependence on a fiber-optic network

The evolution from 4G to 5G is expected to be an even bigger shift in network capabilities compared to the previous generations – this time going beyond traditional consumer applications to advanced consumer and industrial services. It promises enhanced mobile broadband (eMBB) with peak rates reaching 1Gbps; ultra-reliable low latency communication (uRLLC) with low latency in the range of <1ms and 99.999% reliability, and enormous scalability. An operator's ability to realize the full capability of 5G depends on many factors, such as frequency of spectrum, wave propagation characteristics, bandwidth, throughput and coverage. Appendix A has a more detailed discussion of these factors that will determine the number and location of macro and small cells and the associated backhaul[5] connectivity needed.

Higher-frequency bands mean smaller cell coverage areas and greater potential obstacle penetration and line-of-sight issues. But on the other hand, higher-frequency bands also have more bandwidth available and, consequently, can offer higher throughput. Lower-frequency bands have larger cell coverage areas with reduced obstacle penetration issues, but also lower bandwidth available leading to lower throughput. High throughput requirements generally result in more densely packed cells i.e., smaller inter-site distances (ISDs).

Smaller ISDs are more cost-effective in dense urban, urban or suburban areas, where the cost can be spread across more users in a smaller geographical footprint. Larger ISDs will be more cost-effective in suburban and rural areas, where more users can be served over larger areas. Deploying 5G cells using high-frequency bands with short coverage distances would not be economical in rural areas (except possibly to cover isolated hot spots), due to the large number of cells that would be required to effectively cover all subscribers.

Backhaul needs for 5G are expected to be in the range of gigabytes per second as opposed to a few hundred megabytes per second with LTE and about 1Gbps for LTE Advanced. Clearly, copper-based backhaul will not be adequate for this. Therefore, operators need to consider microwave or fiber solutions for backhaul. Today's microwave links operating in the 7–40GHz range can support up to 1Gbps. Beyond 1Gbps will require the E-band (60GHz) or V-band (80GHz) microwave. E-band is unlicensed, while V-band is

5 For the purposes of this analysis, we are assuming that the networks have integrated baseband units, and we are therefore focusing only on the backhaul.

lightly licensed. Upfront capital expenditures will be low for the microwave option. However, licensing costs can be quite high. Moreover, the applicability of microwave for 5G will be constrained by the need for a line-of-sight requirement and potential interference from environmental factors. For the high throughput and low latency requirements of 5G, microwave can at most be used for a single hop,[6] thereby increasing the density of fiber or core transport points of presence. Therefore, a strategy that operators may consider is to have a hybrid fiber and microwave architecture where fiber goes deep into the network and cell sites with microwave backhaul are positioned in such a way that they are less than 1km and one hop away from the fiber-optics network access.

Whether operators choose an all-fiber or a hybrid microwave–fiber strategy, there will be a need for significant investment in fiber to densify the networks. How much they need to spend will depend on specific situations and is a function of morphology, availability of existing fiber, spectrum availability for microwave, and the viability of line-of-sight installations for the microwave. Bell Labs Consulting has developed models to estimate the amount of fiber that is needed for 5G deployment under different conditions and to simulate the implications on operators' financials and are discussed below.

Investment implications and impact on operators

Bell Labs Consulting developed models considering all the factors that impact the number of cell sites needed and simulated a market an operator would operate in. We assume that the market is represented as a composite of morphologies ranging from very dense urban areas to rural areas. Furthermore, since an operator will typically start deploying 5G radios on existing cell sites before it starts adding new sites, we assume that its user base is already served by a grid of 3G or 4G cell sites.

With this starting point, we estimate the total number of additional sites that will be needed. The number of cell sites needed is determined by both coverage and capacity needs. Download speeds determine the capacity needs, while uplink speeds typically limit the coverage distance, as the user end devices have limited power to send data in the radio uplink over long distances. When 5G is initially deployed for coverage, uplink speeds are used to determine the minimum number of sites needed for coverage. Implicit in this is the assumption that since the population is already covered by 4G, there will enough capacity available in the 5G network in the near term. However, as demand grows in the future, more sites will be needed. Depending on the frequency range and spectrum available, the amount of capacity needed can grow manyfold and pose a challenge. For 24+GHz, not only does the peak throughput increase (due to hundreds of megahertz or even gigahertz of bandwidth), but the spatial density of deployment due to a significantly reduced range may also increase. As a result, the density of backhaul capacity (Gbps/km^2) is increased manyfold over LTE.

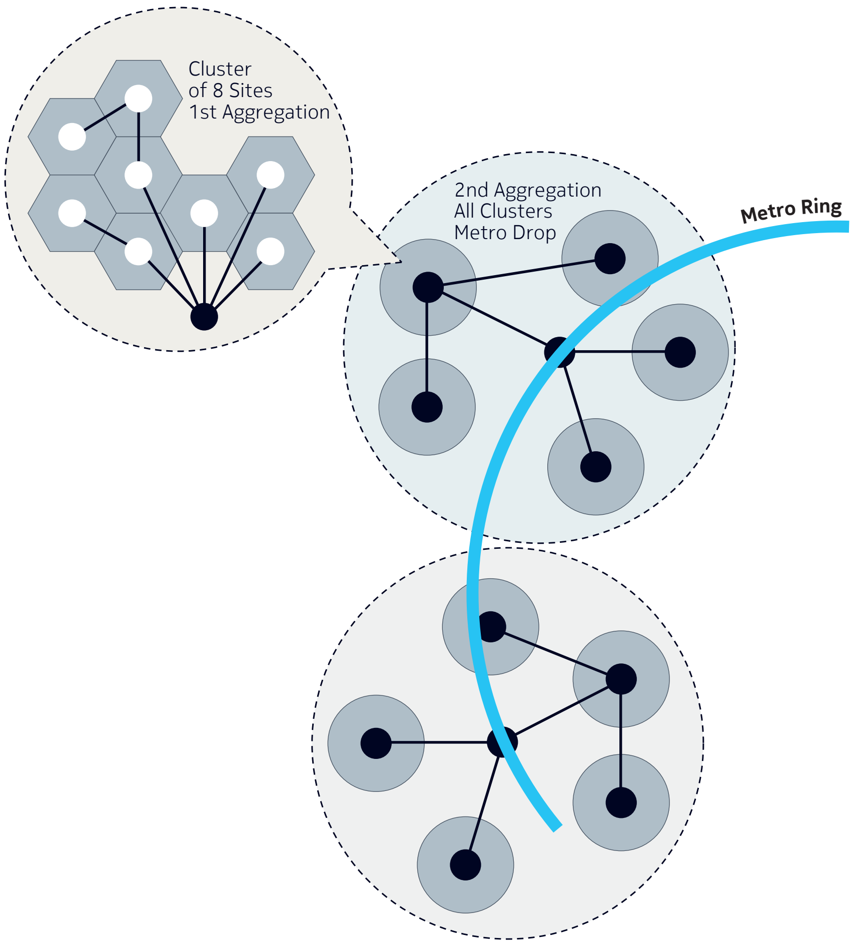
All these additional sites need to be provided with backhaul connectivity with either fiber or high-frequency microwave.[7] The number of connectivity links and the amount of fiber needed will depend on how these links are aggregated and eventually connected to the metro and backbone rings. To minimize the number of connections and fiber needed, backhaul links from clusters of sites are aggregated at certain aggregation nodes. Links from these aggregation nodes may be further aggregated before they connect to the metro ring. Figure 5 shows a typical connectivity arrangement. The exact layout and levels of aggregation will depend on the presence of metro rings and a fiber distribution network, physical barriers, etc.

6 Reliability requirements will limit the distance of the single hop.

7 Wireless self-backhaul, where the exceedingly large bandwidth afforded by millimeter wave is used to serve both access and backhaul, is being considered as yet another alternative for backhaul. With a reduced coverage area, there may not be enough traffic demand to fill the airway pipes, and excess capacity will be available for backhaul. Further, since there is some flexibility in placing millimeter wave sites, a line-of-site link with much higher spectral efficiency can be guaranteed. With wireless backhaul, the speed and ease of deploying millimeter wave is also improved.

In our simulation, we assume that cell sites are distributed evenly in the morphology and we consider two scenarios. In the first scenario, we assume that there are enough metro rings passing through the region under consideration, which is typical of mature economies. In the second scenario, metro ring presence is sparse, which is typical of many emerging economies.

Figure 5. Cell aggregation



We assume that the operator currently has approximately 2,500 LTE sites covering 6 million users in a market and is planning to deploy 5G in the 3.5GHz spectrum with an average uplink speed of 5Mbps to offer eMBB services. Current cell site distribution across morphologies and the average ISD are as shown in Table 3 below.

Table 3. Morphology distribution and inter-site distances

	Very dense urban (VDU)	Dense urban (DU)	Urban (UR)	Suburban (SU)	Rural (RU)
% of cell sites	2%	39%	35%	12%	10%
Average inter-site distance (ISD), km	0.14	0.70	0.95	1.13	3.57

In an actual deployment, there will be a range of ISDs within each morphology. However, for simplicity, we assume that the sites are distributed uniformly in the existing grid within each morphology with an average ISD.

Table 4 illustrates the increase in sites over an LTE grid for 5G coverage as a function of morphology and uplink speeds.

Table 4. Percent increase in sites needed (beyond current LTE grid)

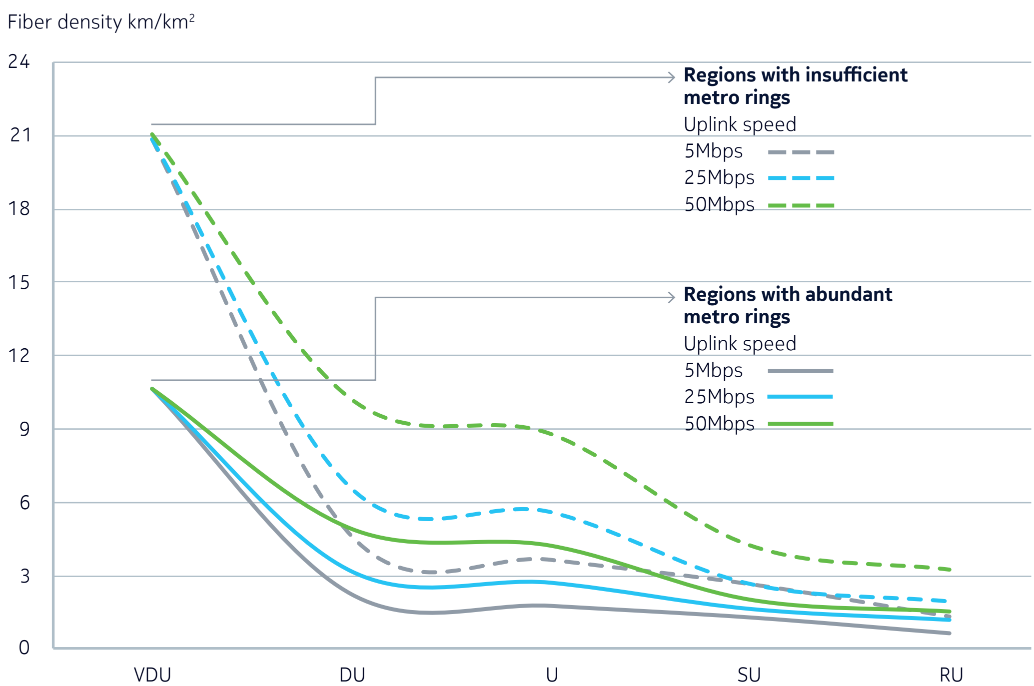
Morphology	VDU	DU	UR	SU	RU
Uplink 5Mbps outdoor	None	16%	34%	None	146%
Uplink 25Mbps outdoor	None	135%	215%	61%	754%
Uplink 50Mbps outdoor	2%	466%	675%	307%	2,266%

We see that for a 5Mbps uplink scenario, the rural and urban areas require a significant increase in 5G sites. However, the very dense urban area does not require any additional sites because the current LTE grid, driven by capacity needs, is already quite dense. As the uplink bandwidth requirement increases, we see an explosion in the number of sites required. Note that if the operator wants to provide uRLLC, it may have to deploy additional sites in dense urban areas as well.

In the extreme case, all these sites must be provided with fiber connectivity. The associated investment will be proportional to the fiber density (kilometers of fiber in one square kilometer)), mainly driven by trenching costs in case of underground deployment.

Figure 6 shows the fiber density needed for different morphologies.

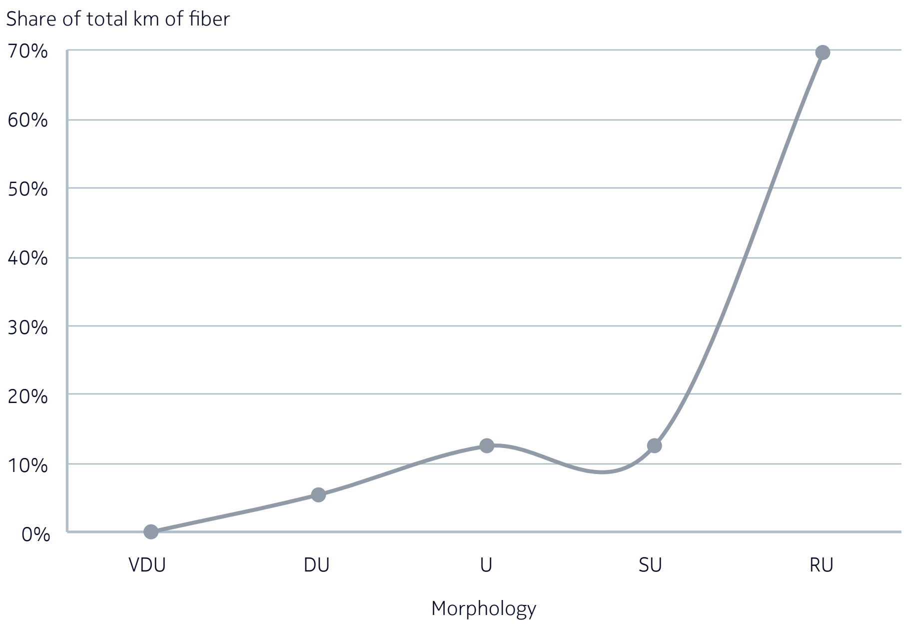
Figure 6. Fiber density required for different morphologies (fiber km/km²)



Unfortunately for operators, very dense urban (VDU) and dense urban (DU) areas, where fiber deployment costs are much higher, also require high fiber density. Where possible, operators are likely to choose microwave. However, given the 5G throughput and latency requirements and limitations of microwave, even if they use the high-frequency microwave links, they will be limited to short one-hop microwave links to a nearby cell with fiber presence. Even with microwave, operators in most countries will have to make significant infrastructure investments to get fiber as close to cell sites as possible. The amount of new fiber needed will depend on the amount of fiber that is already present to connect existing sites and the number of new sites that will be needed for 5G. Operators wanting to deploy 5G will mostly focus initially on very dense urban, dense urban and urban areas, where the existing LTE grid of coverage and capacity sites will provide adequate co-location sites and backhaul for 5G with significantly low cell range. The bigger challenge will arise when lower population density rural areas are targeted for 5G deployment. The existing LTE grid may not be enough to provide adequate coverage for 5G, and significant new investments will be needed. In such cases, operators may need to consider alternate business models such as infrastructure sharing or leasing fiber from wholesalers.

In most mature economies, the very dense urban and dense urban areas already have significant fiber, and most of the new fiber will be needed in suburban and rural areas. Figure 7 shows the share of new fiber needed in different morphologies for an operator that has enough fiber coverage for all existing sites in urban areas and less than 30% coverage for existing sites in suburban and rural areas. Even though the fiber density needed is low for rural morphologies, their share of fiber kilometers is quite high, as the ISDs are large for the rural area, and the total amount of area that falls in the rural category is also very large. This makes the economics of 5G coverage for basic eMBB services in rural areas very challenging.

Figure 7. Share of new fiber needed to provide 5G coverage by morphology



The challenge is exacerbated for emerging economies where fiber presence is limited. Around the world, many regulators require operators to provide universal service, making it a real challenge for operators to provide adequate coverage economically. Countries differ significantly in terms of population densities, habitable land area and morphologies. Given the densification required for 5G, operators can face significant challenges in catering to large populations, and the investment required can have a detrimental impact on their financials. These are essential considerations ahead of 5G auctions, for regulators and mobile operators alike.

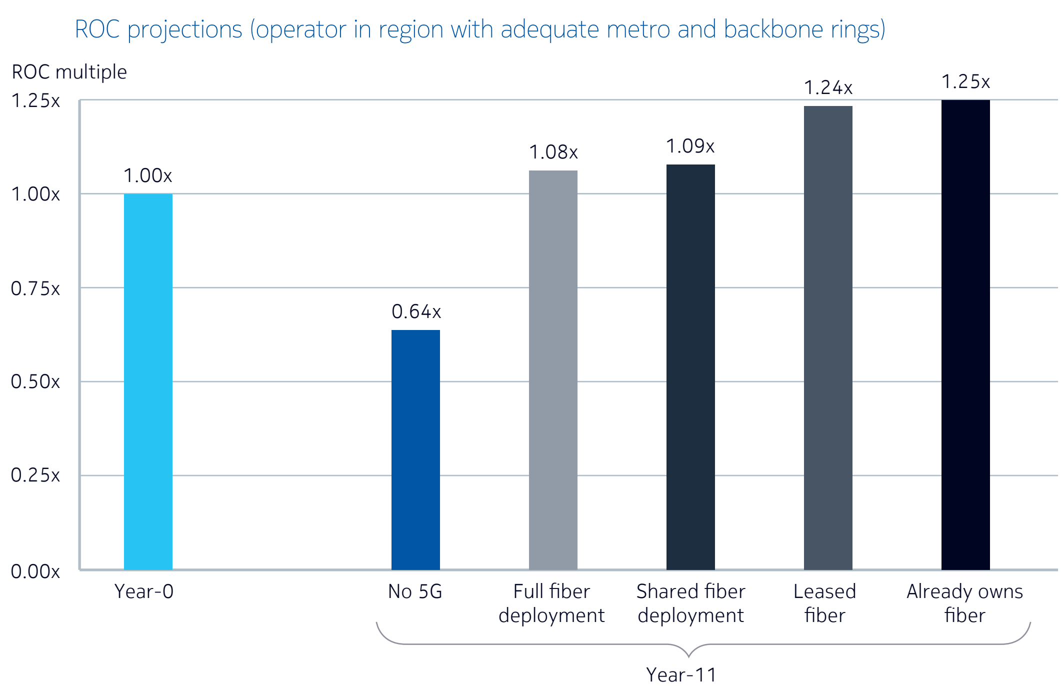
Implications for operator financials

To better understand what this means for operators, we first looked at 5G deployment in a region with the same morphology distribution as shown in Table 3 and with adequate metro ring presence, which is more representative of a mature economy. We will invert this assumption later to consider the case for an emerging economy. We assume that 5G deployment happens in a gradual fashion starting with existing LTE sites followed by additional sites, over a five-year period. We also assume that there is a 6-month lag between deployment and the acquisition of customers, and that in a 10-year time frame 50% of the subscribers are migrated to 5G while the remaining stay with 4G services.

From a revenue perspective, if the operator does not deploy 5G to offer competitive performance and enhanced user experience, then the average revenue per user (ARPU) will continue to decline along the current trajectory of 2% drop per year. 5G, along with edge clouds and digital value platforms, will be a key enabler of the Fourth Industrial Revolution, positioning operators to go beyond traditional connectivity services. Specifically, operators can monetize their ability to provide scalable control (e.g., with private networks) and tailored content (e.g., with digital value platforms hosted at the network edge) to industry verticals. With 5G services, operator ARPUs are assumed to grow by approximately 3% per year – slightly over the average economic growth rate. In addition, we assume that with 5G, and its network slicing capability, the operator will be able to charge a premium to a small subset of customers for customized on-demand services, along with revenues from platform enablement and value-added services. The net result of this is that the operator will double the revenues from the enterprise segment and increase the revenues from the consumer segment by 25%, resulting in a Year-11 revenue that is 1.5 times the Year-0 revenue. By creating vertical-specific solutions that improve productivity and efficiency for the Industry 4.0 era using new digital value platforms hosted in the edge cloud, the operator will be able to emulate some of the cloud/platform players' business models and get a jump in return on capital (ROC).

We compare the ROC implications of deploying 5G under different scenarios: (1) the operator deploys all the fiber needed; (2) the operator shares fiber and deployment costs with another operator; (3) the operator leases fiber from a wholesaler; and (4) the operator already has enough own fiber (i.e., no additional investments for fiber will be needed). In doing this analysis, we assume that the backhaul needs of 30% of all 5G sites can be addressed via a single hop 80GHz microwave link. The ROC implications of the different scenarios are shown in Figure 8 below.

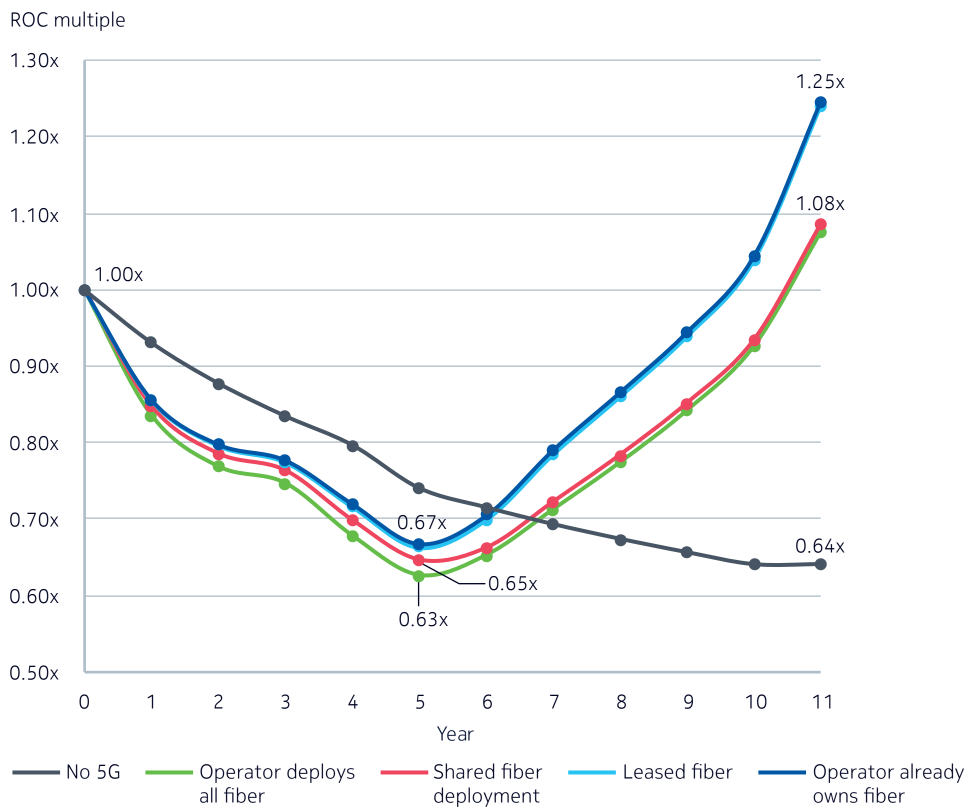
Figure 8. Year-11 ROC projections for different fiber deployment operator strategies in regions with adequate metro and backbone rings



At one extreme, if the operator does not deploy 5G, its ROC will drop by 36% in 10 years, primarily driven by revenue erosion and compounded by the need to continue investing in the network to support traffic growth. At the other extreme, if there is already enough fiber for backhaul, new fiber deployment costs are not incurred and the operator's ROC will increase by 25%. In case the operator does not have own fiber and deploys all the fiber alone, the ROC in 11 years increases marginally but is still much higher than the case with no 5G. Clearly, if the operator can share the capex investment with another operator, the ROC improves, and with the leased fiber option, the operator is able to achieve the same ROC levels as an operator that already owns fiber.

However, looking at the Year-11 view alone belies the stress that operators will have to go through during the rollout phase. Figure 9 shows the year-over-year ROC impact over the 11-year period for different scenarios.

Figure 9. ROC projections for an operator in a region with adequate metro and backbone rings

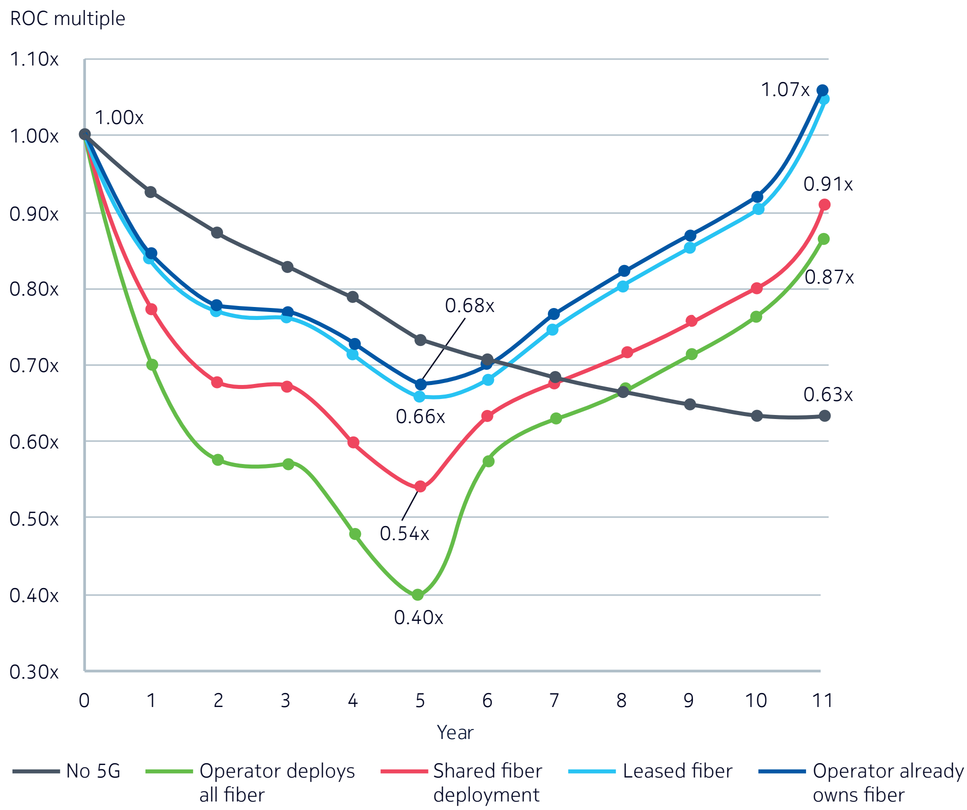


As one would expect, during the 5G rollout phase in the first five years there is a significant deterioration in ROC, which reflects the additional capex incurred and the gap between the deployment and migration of customers to higher-revenue 5G services. The drop in ROC varies with the strategy adopted for fiber connection. Operators that go it alone for fiber deployment will see as much as a 37% drop in ROC in Year-5 compared to the initial (Year-0) ROC.

This drop in ROC will be more pronounced in the regions where metro rings are sparse, as in many emerging economies . Moreover, emerging economies lag mature economies in digital transformation and do not have a sufficiently developed ecosystem to take advantage of the advanced services. Therefore, operators in these countries are likely to limit deployment to the dense urban and urban areas only, where they can expect demand for advanced services. The overall uplift in revenue due to 5G will be lower than what we can see in a mature market.

Figure 10 shows the ROC projections over an 11-year period for an operator in an emerging economy that is deploying 5G. We assume that the current LTE network is identical to what we had assumed for the mature economy case. However, given the limitations on fixed infrastructure, metro rings are sparse and fiber connectivity is limited to 30% of sites in very dense urban areas, 20% in dense urban areas, 10% in urban areas and none in suburban and rural areas. Moreover, we assume that the operator will deploy 5G only in urban, dense urban and very dense urban areas, where end users are likely to demand and pay for 5G services. We assume that the ARPU uplift from 5G service will be two-thirds of what an operator in a mature economy will get. We also assume that revenues from private networks, platform enablement and value-added service revenues will be 30% of a mature economy equivalent. The net result is that Year-11 revenues will be 1.25x Year-0 revenues.

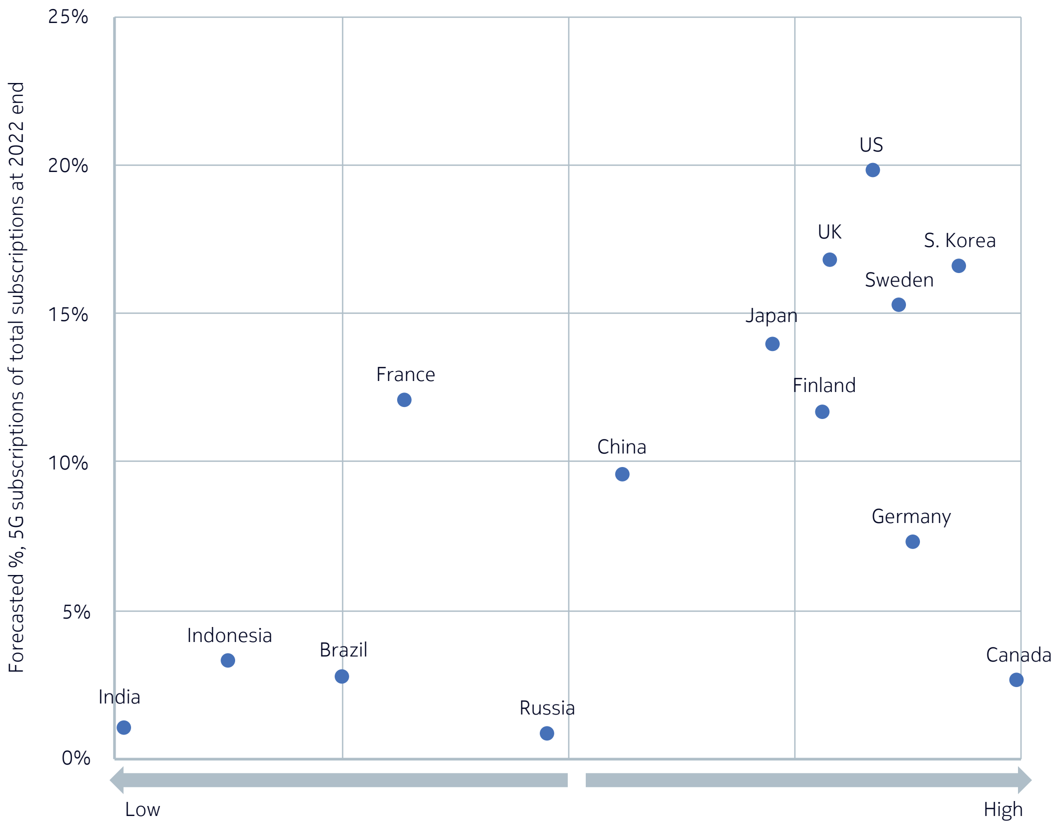
Figure 10. ROC projections for an operator in a region with insufficient metro and backbone rings



Operators that deploy all the fiber needed by themselves will see a 60% drop in ROC during the first five years of deployment. Most operators today operate with a ROC range of 1–12%, and their cost of capital is in the range of 6–11%.[8] This means that most operators already do not earn a healthy economic return (ROC minus cost of capital). Hence, the potential steep decline in ROC with 5G deployment will be financially untenable for most operators, as financial markets will punish them with low valuations and even increase their cost of capital. It is therefore not surprising that the early 5G announcements are primarily coming from operators in countries that already have high fiber availability, as shown in Figure 11.

8 ROC and weighted average cost of capital (WACC) data from http://people.stern.nyu.edu/adamodar/New_Home_Page/data.html.

Figure 11. Projected 5G offtake as a function of fiber penetration



Other countries with high fiber penetration are likely to quickly follow the leaders. However, the big question is how operators in emerging economies with very little current fiber penetration will catch up. Clearly, the industry and these economies need innovative investment strategies to deploy 5G. Given the tremendous amount of capital outlay needed, governments need to play a significant role in stimulating and facilitating investment in fiber as well as help to accelerate 5G deployments.

Recommendations: addressing the “tragedy of missing commons”

Let us first summarize the relevant techno-economic considerations:

1. The new digital era will be enabled by five digital infrastructure networks – (1) energy, (2) health, (3) transportation, (4) communication and (5) production (or manufacturing).[9] With its momentum building up, 5G is a core digital communications technology that will enable the other four digital infrastructure networks and spur the Fourth Industrial Revolution.
2. Dense cellular 5G architecture means more nodes (base stations) and a deeper fiber network. The biggest challenges of incremental fiber deployment are cost and time for securing rights of way and carrying out the civil works.

9 Saniee et al., “Will productivity growth return in the new digital era?”

3. Like the prior fixed networks build-outs, fiber rollout is a high sunk cost and low marginal cost investment with very long payback periods. The analysis shows a significant decline in ROC in the interim years before reaching the payback period.
4. Since first movers can rarely charge monopoly rents forever for highly valuable common utility services, there is very little incentive for competing operators to make large-scale private investments in such a project. Duplicating fiber networks is both wasteful of resources and will lead to unhealthy over-competition.
5. In many parts of the world, particularly emerging economies, operators' balance sheets and cash flows are not conducive to undertaking the required investments.
6. Without enough fiber deployment, the promise of 5G to spur the next industrial revolution will not be fully realized. Hence, accelerated fiber deployment is in the common public interest.

Clearly, this calls for some variation of a shared common fiber infrastructure that fosters healthy competition among the service providers without straining their balance sheets.

In 1968 ecologist Garrett Hardin wrote about the "tragedy of the commons," referring to the phenomenon where unfettered use of a common resource by individuals driven by their selfish interests depletes and degrades the common resource.[10] In economic terms, this can be seen as a game where "Costs are Commonized and Profits are Privatized (CCPP)," leading to no incentives for any player to invest in preserving the commons. In the case of fiber, we already have evolved models to share it among competing players and the CCPP model would work well for all participants. In the absence of adequate fiber density for wireless networks, we have an inverse of this tragedy – a "tragedy of missing commons" – where a widely deployed shared fiber network infrastructure is a common that is needed but does not exist, and whose absence in many regions will deprive them of the benefits of social and economic progress that 5G and the new digital era will bring.

Realizing ubiquitous 5G is within reach if we have ubiquitous fiber commons. Consider as an example the city of Stockholm in Sweden, where at the city's initiative in 1994 it set up Stokab, a public body that laid a city-wide fiber network that currently reaches 90% of the homes and 100% of the businesses. It is no surprise that Stockholm was one of the first cities in the world to be 5G-ready. A recent FTTH Council Europe study[11] that carried out an economic analysis like ours claims that where you already have FTTH, the incremental costs to make the network 5G-ready are marginal – you virtually get 5G fiber connectivity for free. The idea behind "fiber commons" is that it makes economic sense for the costs of fiber deployment (which has a long payback period) to be communized, and for profits from delivering innovative services by competing service providers to be privatized. Thus, fiber commons will ensure that operators and enterprises have open and economical access to fiber for 5G backhaul needs and can focus on the rapid development of service innovations for industrial customers.

Countries and regions differ widely in terms of factors such as the amount of fiber already deployed, service providers' financial health and access to capital, or the degree of competition in the communications industry in urban and rural areas. Hence, there are different paths to achieving the goal of desired fiber commons by region. Nevertheless, we believe that we need the following actions to realize some form of fiber commons appropriate for a region:

10 Garrett Hardin, "The Tragedy of the Commons," Science, New Series, vol. 162, no. 3859 (December 13, 1968), https://science.sciencemag.org/content/162/3859/1243.

11 Raf Meersman, "5G and FTTH: The Value of Convergence," FTTH Conference 2019, Amsterdam (March 12–14, 2019), https://www.ftthcouncil.eu/documents/COM-190313-FibreFor5G-ConvergenceStudy-Presentation-RafMeersman%20-%20v4%20-%20publish.pdf.

1. A top-down vision of the digital future of the country, where a new digital communications network infrastructure enables the four other digital networks, which will drive economic productivity and social well-being – namely (1) health, (2) energy, (3) transportation and (4) production.
2. Translation of this vision into an ambitious infrastructure plan to build or augment “utility corridors” – combining public works, such as the building or maintenance of roads and railroads or the installation of solar panels, with laying conduits for other networks, such as power (electricity and gas), health (water and sewage) and communications (fiber). Defining a new public construction code can immensely facilitate this – for example, a road can be legally defined as one with such utility corridor conduits.

   China’s ambitious plan to install fiber alongside the Belt and Road transportation infrastructure initiative spanning approximately 70 countries is a very prominent example.[12]

   Another relevant example is the relatively new state of Telangana in India, where the initiative to provide running water to its population is combined with laying fiber to get 23 million inhabitants online.[13]
3. A specific, measurable, realistic and time-bound set of goals for the country and planning region for the fiberization of targeted cell sites, taking future needs into account. A National Digitalization Plan should be a superset of the National Broadband Plan; it should cover the five digital infrastructure networks mentioned above.
4. Clear prioritization of investing in the digital future at all levels of government. With notable exceptions such as China and Singapore, most countries lack a consistent digital vision of the future and a clear prioritization of achieving that goal at all levels of government – federal/state/county/municipality. There are many cases of initiatives, legislation and regulations that counter each other – for example, encouraging municipal fiber deployment or allowing power utilities to offer fiber-based broadband services at one level of government is opposed at another level.
5. Addressing incumbents’ concerns about government regulations driving excessive or unfair competition. Incumbents who have invested in fixed infrastructure but not fully upgraded their networks with fiber are concerned that government investment in fiber networks will lead to government competing with the private sector in delivering services to end customers. In the case of regulated service providers, giving them incentives to invest in fiber or collaborate with other dark fiber owners is one approach. Another is providing government-invested dark fiber services to operators at a reasonable cost.

   South Korea, a leader in fiber density, provides interesting policy examples. It started a Korean Information Infrastructure (KII) program back in 1994. One of the components of this program was KII-Government, under which a high-speed backbone network was built so that service providers could use it to provide broadband services to 30,000 offices and 10,000 schools. Later, in 2001–2005, a Digital Divide Closing Plan took the fiber-optic backbone to all the service districts in the country. Most recently, regulators actively moved to prevent excessive competition and unhealthy price wars by encouraging all three mobile operators to share infrastructure and requiring that they all launch 5G service simultaneously.[14]

   In contrast, India’s National Optical Fiber Network to connect 200,000 villages is still in progress,[15] while the Philippines has only recently received a grant for the design of its National Broadband Plan.[16]

12 Susan Crawford, “China Will Likely Corner the 5G Market and the US Has No Plan,” Wired (February 20, 2019), https://www.wired.com/story/china-will-likely-corner-5g-market-us-no-plan.

13 Huizhong Wu, “One Indian State’s Grand Plan to Get 23 Million People Online,” Wired (January 17, 2017), https://www.wired.com/2017/01/telangana-fiber-internet-india.

14 Caroline Gabriel, “Korea Moves to Avoid ‘Excessive Competition’ in 5G, with Lessons for Europe,” Rethink (July 20, 2018), https://rethinkresearch.biz/articles/korea-moves-to-avoid-excessive-competition-in-5g-with-lessons-for-europe.

15 “Bharat Broadband Network – National Optical Fibre Network,” Wikipedia, https://en.wikipedia.org/wiki/Bharat_Broadband_Network#National_Optical_Fibre_Network.

16 Teresa Umali, “DICT Receives USTDA Grant for the National Broadband Plan Implementation,” OpenGov (February 11, 2019), https://www.opengovasia.com/dict-receives-ustda-grant-for-the-national-broadband-plan-implementation.

6. Allowing non-traditional players with fiber assets to offer communication services and partner with established communication service providers. In many fiber-rich countries, the key issues are fragmentation of fiber assets and the urban–rural digital divide. The business case for the incumbent telecom provider to deploy fiber in a less densely populated area may be very weak. However, a local power utility may have already deployed fiber to implement a smart grid and would be in an advantageous position to provide fiber-based communication services either directly or in partnership with incumbent providers. Often, outdated regulations and excessive fear of competition by incumbents come in the way, and these issues should be addressed by governments and regulators.

   An illustrative example is Chattanooga Electric Power Board (EPB), the city-owned utility in Chattanooga, Tennessee. To improve the resiliency of its power grid and better serve its industrial and consumer electric power customers, EPB invested in fiber networks to implement a smart grid. It discovered that its fiber lines running close to the power lines were within 30m of homes, making it easy to offer broadband service to homes.[17] A combination of federal grants and the issuing of municipal bonds provided the necessary capital for the city-owned utility to complete the fiber build and become the first city in the US to offer Gbps speeds, earning it the name “Gig City.”[18] Chattanooga’s rise as a technology and innovation hub has been attributed to the fiber network.[19]

The recommendations and examples above are a starting point. They need to be adapted and refined with further economic analysis to address the needs of a region. Fortunately, the industry has evolved various network infrastructure sharing models (see Appendix A), and we can draw from the growing acknowledgment of best practices (some illustrated in Table 5).

Conclusions

5G wireless, with its promise of delivering fiber-like performance on a massive scale, has raised expectations about spurring the Fourth Industrial Revolution. But deep fiber deployment is indispensable for 5G to realize this vision. We do not have fiber wherever we need it for 5G cell sites, and the economics of each operator investing in new fiber deployments are prohibitive in many markets. Operators in fiber-rich areas have an advantage, yet we need new business models to prevent unhealthy competition. Operators in fiber-poor areas are unlikely to make significant fiber network investments given their challenging business case. Hence, market mechanisms will fail to solve the problem in fiber-poor emerging economies . If we do not address this in time, a new and widening gulf will appear between emerging economies and mature economies. This will be a “tragedy of missing commons,” which can be prevented by creating a common fiber network infrastructure sharable among competing operators. It will serve the interests of consumers, industrials, operators and governments. We call for creative public–private partnerships with public sector leadership to realize the fiber commons.

While there are some noteworthy regional examples of tackling this, China’s aggressive push in fiber deployment stands out. For example, China’s fiber deployment project, tightly coupled to its Belt and Road transportation infrastructure initiative, is a smart and ambitious national government-led agenda. Other fiber-poor countries lacking in such an ambitious vision should treat this as a wake-up call. Many of the fiber-poor emerging economies are still catching up on previous industrial-era network infrastructure investments, such as water, sewage, electricity, gas, road and rail, to cover their under-served regions. It is

17 Jonathan Taplin, “Chattanooga Has Its Own Broadband, Why Doesn’t Every City?,” Daily Beast (July 24, 2017), https://www.thedailybeast.com/chattanooga-has-its-own-broadbandwhy-doesnt-every-city.

18 Edward Wyatt, “Fast Internet Is Chattanooga’s New Locomotive,” New York Times (February 3, 2014), https://www.nytimes.com/2014/02/04/technology/fast-internet-service-speeds-business-development-in-chattanooga.html.

19 Rob Marvin, “Gig City – How Chattanooga Became a Tech Hub,” PC Magazine (May 4, 2018), https://uk.pcmag.com/features/94715/gig-city-how-chattanooga-became-a-tech-hub.

now time to turn this delay into an opportunity to couple these network investments with one in building the fiber commons. This will eventually usher in an era of smart networks and infrastructures to increase economic growth, productivity and social well-being.

Table 5. Illustrative best practices to support a fiber common for 5G

	Practice	Rationale	Examples
1	Access to street furniture and public land for radio heads.	Required to meet site densification needs.[20 21]	Outdoor advertising company JCDecaux will support small cell solutions for 4G and 5G on its street furniture in 10 French cities.[22]
2	Access to buildings and rooftops for radio heads.	Required to meet site densification needs.	Singapore regulator IMDA's Code of Practice for Info-communication Facilities in Buildings (COPIF).[23]
3	Build-out of national fiber backbones where they do not exist.	Required in countries that do not have backbone connectivity to all parts.	• South Korea's KII-Government program started in 1994.[24] • Colombia's Plan Vive Digital,[25] 2010–2018.
4	Cross-sector infrastructure sharing.	"Network sector" industries achieve economies by pooling costs. Utility corridors enable sharing of costs across industrial sectors.[26]	• Early precedent in railways and telegraph lines. • In the US, from the mid to late 1990s, newly formed communication carriers laid 80,000 route km of fiber along the utility's right of ways.[27] • In the newly formed Indian state of Telangana, fiber is being laid along with fresh water pipelines to reach 23 million people.[28]
5	Shared access to passive networks, including regulated passive sharing products if necessary.[29]	Shared access to passive networks achieves lower unit costs. See Appendix A for more details.	• Stockholm's rise as the Silicon Valley of Europe is attributed to their city-owned, passive fiber network.[30] It is also one of the first cities in the world to launch 5G. • National broadband networks with regulated open access for service providers currently in place in Australia, New Zealand, Qatar, Singapore and other countries. • In November 2017 the Netherlands passed a bill that mandated owners of passive networks to support sharing requests.[31]

20 International Telecommunication Union (ITU), Setting the Scene for 5G: Opportunities & Challenges (Geneva: International Telecommunication Union, 2018), https://www.itu.int/en/ITU-D/Documents/ITU_5G_REPORT-2018.pdf.

21 BT's press release "BT Calls for Open, Equivalent Access to Street Furniture to Boost 4G and 5G Coverage" (March 21, 2019), https://www.btplc.com/news/index.htm#/pressreleases/bt-calls-for-open-equivalent-access-to-street-furniture-to-boost-4g-and-5g-coverage-2850529.

22 Juan Pedro Tomás, "JCDecaux to Help French Telcos to Deploy Small Cells in Street Furniture," RCR Wireless News (February 4, 2019), https://www.rcrwireless.com/20190204/5g/jcdecaux-help-french-telcos-deploy-small-cells-street-furniture: "The company said that this decision follows the publication of a report by France's National Frequency Agency (ANFR) in December 2018, demonstrating the relevance of the small cells installed on JCDecaux street furniture."

23 IMDA's Code of Practice for Info-communication Facilities in Buildings (COPIF) has been amended in 2018 to facilitate better access to buildings and rooftops.

24 Robert Atkinson, Daniel Correa and Julie Hedlund, Explaining International Broadband Leadership (Washington: Information Technology and Innovation Foundation (ITIF), 2008), https://www.itif.org/files/ExplainingBBLeadership.pdf.

25 Organisation for Economic Co-operation and Development (OECD), Development of High Speed Networks and the Role of Municipal Networks, Box 9 (2015), http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DSTI/ICCP/CISP%282015%291/FINAL&docLanguage=En.

26 World Bank, Toolkit on Cross-Sector Infrastructure Sharing, Broadband Strategies Toolkit, Module 8 (2017), http://pubdocs.worldbank.org/en/307251492818674685/Cross-Sector-Infrastructure-Sharing-Toolkit-final-170228.pdf. Network sector industries are "industries which provide lateral carriage of people, goods and commodities."

27 Ibid.

28 Wu, "One Indian State's Grand Plan."

29 Body of European Regulators for Electronic Communications (BEREC), Report on the Convergence of Fixed and Mobile Networks (2017), https://berec.europa.eu/eng/document_register/subject_matter/berec/reports/7311-berec-report-on-the-convergence-of-fixed-and-mobile-networks.

30 Ben Schiller, "How Stockholm Is Creating the Second Silicon Valley in Scandinavia – Hint: It's the Super-Fast, Government-Funded Internet," Fast Company (22 June, 2016), https://www.fastcompany.com/3061052/how-stockholm-is-creating-a-second-silicon-valley-in-scandinavia.

31 ITU, Setting the Scene for 5G: Opportunities & Challenges.

6	Incentives for investment in fiber density.	A stimulus is needed to ease the burden of investment in facilities that entail large capex and have long life cycles.	Japan: service providers were allowed to write off about one-third of broadband-related capex in the first year. The Bank of Japan guaranteed debt, making loans cheaper.[32]
7	City- and region-wide databases with key contacts for street furniture and utility ducts.	Central databases will ease rollout and operations and maintenance.	Databases exist in Portugal and Spain.[33]
8	Standardized approval processes and wayleave agreements.	Standardized wayleave agreements and processes will make it easier for fiber assets to be deployed, expanded and maintained.	• City of London's wayleave toolkit.[34] • Some cities in the US have created standardized processes and guides to streamline rollouts.

Appendix A: 5G frequencies, bandwidth and architectural considerations

5G frequencies

5G macro and small cell deployments will ultimately occur in many frequency bands across the broad wireless frequency spectrum. The most common 5G frequencies will be in the 3.5GHz band (centimeter wave), in the 26/28GHz band (also centimeter wave) and in the 39GHz band (millimeter wave). Some 5G deployments may be in the sub-1GHz frequency band and some may be above 39 GHz.

Frequency bands are administered by national or regional bodies such as the Federal Communications Commission in the United States. The choice of frequency bands used by communication service providers will depend on many factors, including coverage, bandwidth capacity, throughput requirements, availability, and acquisition cost.

5G bandwidth

Bandwidth[35] is the range of wireless frequencies on which data traffic is carried. Different frequency bands have different amounts of bandwidth available per operator, which is also allocated by national or regional bodies. 5G bandwidth for frequency bands below 1GHz will typically be limited to about 20MHz. Bands below 6GHz will have up to about 100–200MHz of bandwidth available, and bands above 28GHz will have up to 800MHz available.

The amount of bandwidth, along with the technology modulation efficiency, will determine how much throughput an operator can offer to consumers.

Wave propagation characteristics

Radio wave propagation characteristics at higher frequencies (i.e., above 3GHz) are very different compared to those at lower frequencies (i.e., sub-3GHz). At higher frequencies, such as 39GHz, waves have difficulty penetrating obstacles such as walls and thus have higher penetration loss. This loss results in waves being blocked or significantly diminished in energy if they do penetrate. Even tree leaves that get into the line of sight between wireless transmitters and receivers can impact reception quality. High-frequency millimeter waves generally require a direct line of sight between a wireless transmitter

32 Atkinson et. al., Explaining International Broadband Leadership.
33 ITU, Setting the Scene for 5G: Opportunities & Challenges.
34 Ibid.
35 Bandwidth can also be defined as the amount of data transmitted over a specified time interval.

and a receiver to achieve the best-quality transmission. Millimeter wave frequencies may be limited to transmission coverage distances of only a few hundred meters.

Such is not the case for lower frequencies (i.e., sub-6GHz frequencies), which have better propagation characteristics. Depending on the frequency band used, coverage distances of several kilometers are possible, and penetrating obstacles such as walls and foliage becomes easier.

Wave propagation characteristics at chosen frequency bands determine how close (or dense) macro and small cells are located for a desired 5G wireless coverage footprint, and thus will impact the amount of fiber required.

Throughput

The amount of bandwidth available and the spectral efficiency of modulation determines the throughput that can be provided. Throughput is the amount of data transmitted in a given amount of time, and is expressed in terms of kilobits per second (Kbps), megabits per second (Mbps), gigabits per second (Gbps) or terabits per second (Tbps). Generally with 5G, the higher the frequency band, the greater the bandwidth available and thus the higher the throughput possible.

The targeted throughput is another factor determining cell location density (and how much fiber is required). Locating cells closer to each other allows higher geographical frequency reuse to serve a smaller number of consumers with higher throughputs. Since the transmission power of end user equipment is limited, the objective of increasing uplink throughput is a big driver toward smaller cells.

Architecture considerations

As operators prepare for 5G, Cloud RAN is one of the considerations. Cloud RAN architecture implements parts of the radio access network as virtualized network functions in a data center. In this architecture, the baseband unit is separated into three parts – the radio unit (RU), the centralized unit (CU) and the distributed unit (DU). The RU-to-CU connection is called the “fronthaul,” the CU-to-DU connection is called the “midhaul,” and the DU to the network core is called the “backhaul.” Collectively, the term “X-haul” is used to describe all three connections. If operators choose to take this path, the bandwidth requirements can easily surpass 100Gbps. This level of transport precludes the use of any transport technology but fiber.

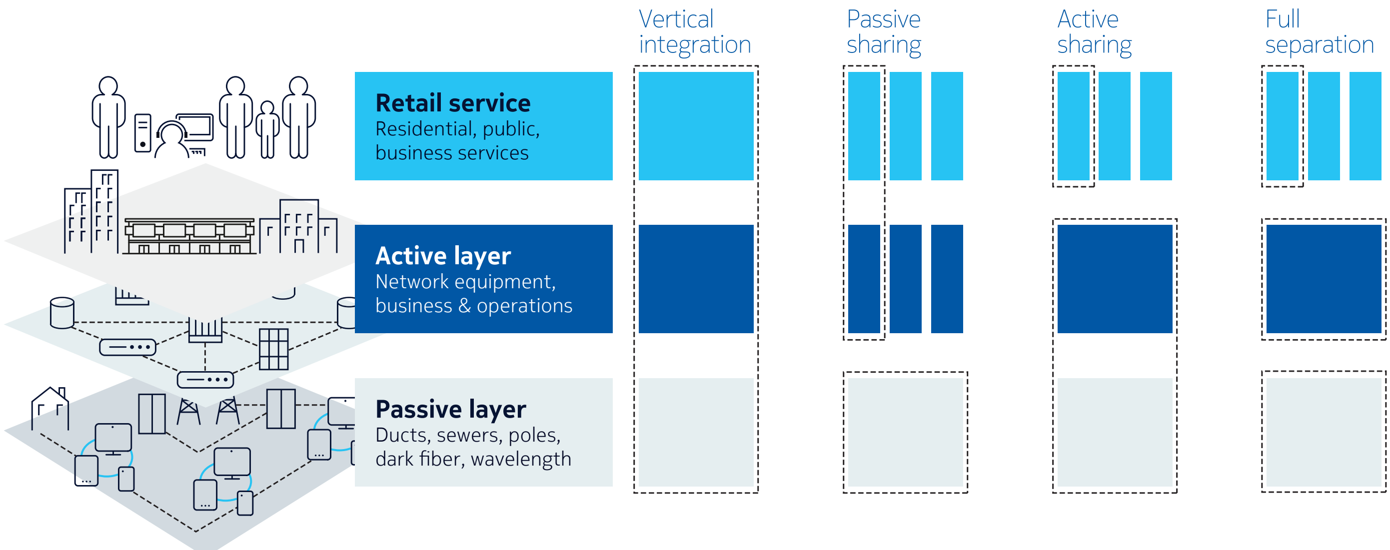
Appendix B: infrastructure sharing models

Some of the network infrastructure sharing models first used in the context of encouraging universal fixed broadband services are informative in the context of fixed density as an imperative for 5G.

There are three approaches to achieving near-universal fiberization of cell sites, and regulators and operators need to assess and choose the right mix of approaches to be 5G-ready. The approaches are (1) vertical integration, (2) market-driven infrastructure sharing and (3) government-driven infrastructure sharing.

Figure 12 contrasts the vertical integration model with three modes of network infrastructure sharing, depending on the possible ways of separating the passive layer, active layer and retail services.

Figure 12. Infrastructure sharing models



The vertical integration model implies no sharing at any level. The passive sharing model is when operators share the passive components of the network while retaining sole ownership of the active components. Active sharing, as the name indicates, also involves sharing of the active network components. Full separation is where the network infrastructure is separated from the retail service layer, with network infrastructure being shared by multiple retail service providers. Each of the three modes of sharing – passive sharing, active sharing and full separation – has established precedents in different parts of the world, with passive sharing being the most common.

Vertical integration is a viable approach for large incumbents and for new entrants with adequate investment capital. Verizon Wireless in the US, NTT in Japan, Orange in France and Telefónica in Spain are examples of incumbents that have predominantly used the vertical integration model in their primary markets. Reliance Jio in India is an example of a challenger in an emerging economy that has laid more than 250,000km of fiber to enable an all-LTE network and has recently launched fixed broadband services in 1,100 cities in the country.[36] Even in regions where vertically integrated operators are viable, the government and regulators can help with policies that encourage stakeholder partnerships, entry of new players like utilities that have dark fiber, or by facilitating access to street furniture or utility poles.

For many operators, however, as densification multiplies site counts by orders of magnitude, there will be a need to share fiber infrastructure to make 5G financially viable. The choice is between a market-driven approach and a government-driven approach, and it may be worth looking at how these choices have impacted fixed broadband penetration. Singapore and Hong Kong, both advanced economies and city-states that perform well on the ranking of internet availability and speeds,[37] present an interesting contrast in approaches to ensuring fixed broadband access. Hong Kong has followed a market-driven model without any subsidies or infrastructure sharing,[38] while Singapore has largely followed a regulator-driven full separation model,[39] with subsidies of about US$750 million having been provided to open access passive and active layer companies that offer services at regulated and public prices. About 15% of Hong Kong's

36 "Jio," Reliance Industries Limited, http://www.ril.com/ourbusinesses/jio.aspx.

37 For example, Akamai and Ookla.

38 Gary McLaren, "Hong Kong's Fibre Broadband Market: Busting the Myth of Residential Fibre Broadband Always Being a Natural Monopoly," Australian Journal of Telecommunications and the Digital Economy, vol. 5, no. 3, art. 117 (2017), http://doi.org/10.18080/ajtde.v5n3.117.

39 "Next Gen NBN," Infocomm Media Development Authority (IMDA), https://www.imda.gov.sg/industry-development/infrastructure/next-gen-national-infocomm-infrastructure/wired/next-gen-nbn.

population does not have fiber-based services, unlike Singapore, where fiber-based services are covered by a universal service obligation. Spain has recently become a European leader in fixed broadband access with market-driven infrastructure sharing.[40] While the incumbent Telefónica has used a vertically integrated approach, its competitors Orange and Vodafone use active sharing by mutual agreement.

In some cases, rather than wait for market forces, governments have taken initiatives themselves. These government-driven models were created with the objective of making broadband access more inclusive. Government-driven infrastructure sharing models exist in Australia, New Zealand, Qatar and Singapore, for example. The same models can be applied to the problem of buttressing fiber availability for mobile operators. The South Korean government, for example, has led an industry initiative for a shared 5G network that will save an estimated US$1 billion in 5G rollout costs over the next decade.[41] The stated aim of this initiative is to cement the nation's leadership in the early commercialization of 5G and the Fourth Industrial Revolution. This approach should be considered seriously by emerging economies where capital availability may be limited for operators to afford large-scale fiber deployments.

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40 Enrique Medina, "Why Spain Is A Case Study for Super-Fast Broadband," Telefónica, https://www.telefonica.com/en/web/public-policy/blog/article/-/blogs/why-spain-is-a-case-study-for-super-fast-broadband.

41 Kim Han-joo, "Mobile Carriers To Share Burden in Building 5G Network Infrastructure," Yonhap News Agency (April 10, 2018), http://english.yonhapnews.co.kr/news/2018/04/10/0200000000AEN20180410009600320.html.

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Abbreviations

1G	first-generation cellular technology
2G	second-generation cellular technology
3G	third-generation cellular technology
4G	fourth-generation cellular technology
5G	fifth-generation cellular technology
ARPU	average revenue per user
capex	capital expenditure
DOCSIS	Data Over Cable Service Interface Specification. An international telecommunications standard that permits the addition of high- band-width data transfer to an existing cable television system
DU	dense urban
eMBB	enhanced mobile broadband
FTTH	fiber-to-the-home
FTTX	fiber-to-the-X; includes fiber-to-the-home, fiber-to-the-curb and fiber-to-the-neighborhood
Gbps	gigabits per second
GDP	gross domestic product
GHz	gigahertz
HH	household
ISD	inter-site distance
Kbps	kilobits per second
Km	kilometer
LTE	long-term evolution
Mbps	megabits per second

MIMO	multiple-input, multiple-output. Refers to a practical technique for sending and receiving more than one data signal simultaneously over the same radio channel by exploiting multipath propagation
ms	millisecond
MSO	multiple system operator (cable TV operators)
ROC	return on capital
RU	rural
SU	suburban
T1	Transmission System 1. Data circuit that runs at the 1.544 Mbps line rate
Tbps	terabits per second
UMTS	Universal Mobile Telecommunications System
UR	urban
uRLLC	ultra-reliable low-latency connection
VDSL	very high-speed digital subscriber line
VDU	very dense urban
WCDMA	Wideband Code Division Multiple Access

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