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5G Mobile Broadband:
The Economic Potential and Policies that Maximize It

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1 Introduction

1. IHS Markit's study on the economic impact of 5G finds that between 2020 and 2035 5G technology will have an impact on global GDP that is roughly equivalent to adding an economy the size of India to the present global economy. They find that the "value chain" associated with 5G technology will amount to $3.5 trillion (in today's dollars) of output and 22 million jobs. They further find that another $12 trillion of output will be "5G-enabled"—i.e., this is the increase in output that 5G enables across a swathe of economic sectors.

2. In this piece, we provide some economic context to these findings, and develop their policy implications. The considerable economic literature on General Purpose Technologies (GPTs) provides a means to assess and contextualize the findings of the IHS study. At least as importantly, it provides some insights into some critical dimensions of public policy that could impact on the magnitude of the gains from 5G. If it is correct to postulate that 5G mobile broadband will have characteristics similar to those of GPTs, then one can expect that the gains from 5G will eventually (although after a period of time) be very large. Not only do IHS' projections of potential economics gains from 5G appear reasonable and arguably even conservative in this light, but they give rise to the concern that poorly designed public policy could impact adversely the speed and magnitude with which these gains are realized. We emphasize this policy perspective in our piece.

3. 5G technology will put mobile broadband at the centre of a global economy characterized by the "Internet of Things." Mobile broadband in the 5G era will transition from being an increasingly significant enabling technology into a true "General Purpose Technology"—that is, a technology that finds economy-wide use, drives complementary innovations in other sectors and becomes a driver of economy-wide innovation and productivity. Whether 5G quite meets some strict epistemological criteria for GPTs is less relevant to us than the fact that 5G will make mobile broadband a key medium through which devices are connected, information is transmitted, transactions are facilitated and new connected activities are enabled. Given these characteristics, the economic literature on GPTs provides highly relevant insights into the nature and magnitude of the expected impact of a technology such as 5G. The literature clearly suggests that the ultimate economic impact of GPTs is very large. However, the literature also makes it clear that the impact of a GPT accumulates over time—the impact of railroads in England and Wales in 1859 was estimated at 4% of national income but at 10% of national income in 1890, indicating that the impact of railroads ramped up over time. The impact of Information and Communications Technology (ICTs) in the 1990s was actually even larger than the impact of previous GPTs and arguably occurred with less of a lag. One does not need to postulate that 5G will be as important as railroads in the 19th century or indeed ICTs in the 1990s to appreciate that it will have a very sizable economic impact—even a fraction of the impact of these past GPTs would still be enough to make 5G a significant enabler of growth in the coming 2 decades.

4. Intuitively, technologies that are GPT-like require complementary innovation and investment in other sectors in order to achieve their maximum impact. The impact of computers famously

could be seen everywhere except the productivity statistics in the late 1980s.[3] But by the late 1990s, ICT was contributing perhaps 1 percentage point per year to U.S. GDP growth. It took a while before firms adjusted their business models, invested in retraining their workforces and managers, and realized the full range of business transactions that could be conducted more productively using ICTs. Likewise, the impact of 5G will play out over a period of time. [[**For the 2020-2035 time period, 5G will contribute an average of 0.2 percentage points per year to global GDP growth. Given projected annual growth of 2.9% per year, this is around 7% of all growth during this time period**]]. This is quite an appreciable GDP impact in its own right, although experience with other GPTs suggests that impact is likely to be even greater in the period following 2035. Whereas the impact in the 2020s will be largely driven by capital investment and R&D expenditure within the investing sector, in the 2030s it will be increasingly driven by the ramp-up of productivity or complementary innovation in 5G-using sectors. These projections fit with the documented experience regarding the impact of other GPTs.

5. The economic literature on innovation and on GPTs also suggests that with many significant innovations—and certainly with GPTs—the social rate of return greatly exceeds the private rate of return. In simple terms, what society gets is far above what the innovator or investor in the GPT gets. One can sensibly expect this to be the case for 5G as well—economic literature on the impact of past telecommunications technologies suggests that the social rate of return could be between 2 and 6 times the private rate of return. Further, the full impact of a GPT is recognized only when there is a significant amount of complementary innovation by other sectors—i.e., by "using" sectors that use 5G as a platform.

6. From a public policy perspective, this provides two crucial insights: first, the private incentive of technology owners or developers to invest in a GPT is too low relative to the social incentive for such investment to occur, and second, the need for technology owners or developers to facilitate complementary innovations further suggests that they will struggle to capture a particularly high share of the social value of the technology. These stylized facts about GPTs sit uneasily with the perception—particularly evident in antitrust policy—that owners of standards-essential IP are in a position to exercise significant market power and thus extract an inefficiently high proportion of the social surplus from innovation. In the 5G context, one can reasonably expect that technology licensors will recognize the need for downstream implementers to have incentives to develop complementary technologies, implying incentives to license widely (even absent any policy-related constraint such as FRAND licensing requirements) and also implying that only a relatively modest share of the social surplus from 5G will accrue to upstream technology developers.

7. Beyond policy that affects the incentives to engage in fundamental research related to the development of 5G, there are policy variables that impact upon the deployment of the technology by the telecommunications sector. In too many countries, spectrum policy is sometimes viewed purely as a tool for generating revenues for the exchequer. Even without this view, spectrum policy in some developing countries (particularly) has erred too much in

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[3] The Nobel Laureate and growth theorist Robert Solow famously remarked to the New York Times in 1987 that "You can see the computer age everywhere but in the productivity statistics."

restricting operators' access to spectrum based on fears of operators' market power. These policy barriers can slow and reduce the realization of benefits from 5G deployment.

2 GPTs and Enabling Technologies: Key Economic Attributes

2.1 Defining GPTs and Enabling Technologies

8. The proposition that 5G will enable mobile broadband to become a GPT or at least a reasonable approximation to it is the key construct underpinning the IHS study. Fully appreciating the potential economic impact of 5G technologies thus requires an understanding of the nature of GPTs. Teece (2017) provides the following discussion:

> *Bresnahan and Trajtenberg (1995) and Bresnahan (2012) identify a GPT by the following three characteristics. GPTs (1) are pervasive, i.e., in wide use; (2) are capable of ongoing technical improvement; and (3) enable complementary innovations in application sectors. In other words, GPTs have economy-wide effects, get even better, and spawn other innovations because invention in one area triggers discoveries and creates opportunities elsewhere.*

9. ICTs provide a much-studied recent example of a GPT. ICTs—computers, telephones and the Internet—are used throughout the economy. Although the Internet existed in the 1970s and 1980s, it was not until the 1990s that it was fully commercialized, reflecting a marriage between the previously discrete worlds of computing and telecommunications. Starting in the 1990s, a dominant share of telecommunications operators' capital investments were in technologies designed to increase the capability of networks to support data transmission at high speeds. Technology hardware firms—most notably handset makers—also began to invest in developing products specifically designed to take advantage of broadband networks, as most clearly seen in the smartphone revolution that started in 2007. As will be evident to most readers, the improvements in networking, communications and hardware were supported by continued rapid improvements in processing speeds, and accompanied by rapid development of software and apps, and rapid transformation of the business models of a vast range of industrial sectors, from retail to finance.

10. It was not until the late 1990s, however, that the impact of ICTs in the productivity statistics, especially in the U.S., became fully evident. This is entirely consistent with the typical relatively slow initial diffusion and impact of GPTs, and also consistent with the role of "complementary capital" in enhancing the impact of investment in the GPTs themselves. Brynjolfsson and Hitt (2000) find that significant increases in productivity occurred when computerization was combined with significant investment in other types of assets—new business organizational processes and structures, and retraining or recalibration of the workforce. Other examples of prominent GPTs are steam power, railroads and electricity.

11. The literature also considers "enabling technologies" that have a large impact primarily in the sector in which they originate. For example, containerization of cargo shipping boosted shipping productivity immensely, and by doing so also boosted international trade and GDP (Teece (2016)). Since the basic technology remained stable and did not really spawn complementary innovation (but merely facilitated shipping of existing products) containerization does not meet the strict criteria for being a GPT. But it certainly had a large macro-economic impact.

12. Mobile broadband technology, as implemented to date, has some GPT-like characteristics—its pervasiveness, its continued improvement, and its use as a "platform" upon which many complementary software innovations are based. However, in many cases, mobile broadband serves as an "adjunct" or complement to fixed broadband—e.g., it is doubtful that the smartphone revolution would have occurred at the time it did and to quite the same degree were it not for these devices' ability to tap into fixed broadband networks (via Wi-Fi routers). Historically, businesses have also relied on fixed broadband networks for their high-speed data transmission needs—with the most sophisticated ones meeting their needs by using expensive dedicated fibre connections to their premises.

13. Thus the impact of mobile broadband per se has arguably been greatest in the communications and software sectors, with its economy-wide impact difficult to distinguish from the impact of all broadband technologies more generally. **[[**IHS' report points to 5G technology's ability to provide very low latency, combined with its flexibility (the ability to operate in both licensed and unlicensed spectrum) and the fact that specific aspects of the 5G standard are being purpose-built to integrate into the Massive Internet of Things (MIOT). These facets of 5G will as IHS also points out, will enable mobile broadband to move from a communications technology with relatively limited industrial applicability to something much more similar to a GPT.**]]**

2.2 Empirical Evidence on the Impact of GPTs and Significant Innovations

14. There is a large empirical literature that is related to GPTs, to the impact of industrial innovations, and the impact of previous waves of telecommunications and ICT technologies. We provide a very brief review of four main strands of this empirical literature, which we also summarize in **Table 1**.

2.2.1 Literature on the historical impact of GPTs.

15. Literature on the impact of historical GPTs is of two varieties. First, there is the literature pioneered by economic historians on the "social savings" from past waves of GPTs. "Social savings" is essentially a reference to the reduction in resource costs—equivalent to the gain in national income—from using a particular technology relative to its next-best alternative. In the context of railroads, these savings amounted to as much as 10% of national income in some countries (Crafts (2004)).

16. Second, a more recent and much-studied GPT was Information and Communications Technology (ICT). Unlike with steam power and railroads, the impact of ICTs was frequently captured through "growth accounting" studies. These studies break down economic growth into its component sources: increases in the labour force, increases in the capital stock (or more precisely, the flow of capital services), and increases in the productivity of the factors of product (total factor productivity or TFP). ICT contributes to economic growth in two ways—first, investment in ICT assets increases capital ("capital deepening"), and second, ICT leads to increases in total factor productivity. By one set of growth accounting estimates for the United States—Jorgenson and Vu (2016)—increases in ICT capital accounted for about a 1% increase in GDP each year between 1995 and 2000. Improved total factor productivity provided a similar increase (roughly). Given annual average growth of around 4% a year in the 1995-2000 period, and the reasonable assumption that much of the growth in TFP was the result of the diffusion of ICT, ICT accounted for about half (2% a year) of the annual average

growth experienced in this period (which saw the most sustained increased in output, employment and productivity since at least the 1960s).

17. Arguably, the impact of ICTs was greater and more immediate than the impact of some previous GPTs, if one looks at comparable (growth accounting) methodologies. The OECD's 2008 study of the impact of Broadband on the aggregate economy suggests that the annual average contribution to productivity growth of ICTs during the late 1990s (1996-2001) U.S. economic boom was 1.79 percentage points per year, whereas at its peak steam power contributed 0.38 percentage points per year to British productivity growth. [4]

2.2.2 Studies on the economic impact of telecommunications technologies

18. Many studies follow an econometric approach best exemplified in Roller and Waverman (2001). This study carefully accounts for causality and sources of bias in estimating the impact of telecommunications on economic growth. The study finds that the expansion of fixed telecommunications lines accounted for as much as a third of German GDP growth between 1970 and 1990, presumably because of the transition from a low or medium-penetration economy to universal and inexpensive telecommunications over the same time period. This transition likely facilitated significant cost savings and productivity improvements in the wider economy. The World Bank (2009), also using an econometric approach, finds that a 10 percentage point increase in broadband penetration produced a 1.21 percentage point increase in the long-run average GDP growth rate in developed economies and a 1.38 percentage point increase in the long-run average GDP growth rate in developing economies. To put these numbers in context, average annual global growth is typically around 3% to 4% a year. A more recent study by SQW and Cambridge Econometrics (2013) predicts that the projected increases in UK broadband speeds between 2013 and 2024 will add about £17 billion per year in "gross value added" (GVA) or about 0.07 percentage points (in real terms) per year to GVA.[5] A study by Chalmers Institute of Technology (2012) finds that a doubling of broadband speeds adds 0.3 percentage points per year to GDP growth.
19. Additionally, Oliner et. al. (2007) find (using the growth accounting framework) that investment in communications equipment and increases in productivity in the telecommunications equipment producing sector added a combined 0.19 percentage points per year to U.S. labour productivity growth in 1995-2000. Given that productivity growth was 2.51% per year during this period, the contribution of investment in communications hardware and productivity increases in its producing sector was around 8% of all productivity growth during the peak years of the U.S. productivity boom of the 1990s. This is likely an underestimate of the impact of communications technologies, as there is no way in growth accounting studies to capture the interaction between communications and other types of ICT (e.g., computer hardware).

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[4] The contribution of ICT to (labour) productivity growth is the sum of the impact of ICT capital deepening and TFP growth in the ICT-producing sector. This may be an underestimate of the contribution of ICT, because measured TFP in ICT-using sectors may actually reflect "characteristics" of the ICT capital stock. Waverman and Fuss (2005) use an approach which incorporates penetration rates of computers, telecom technologies and network characteristics (e.g., digitalization of the telecom network) to capture "ICT spill over" effects, some of which might be measured as non-ICT-related TFP growth in conventional growth accounting studies.

[5] GDP is equal to GVA plus taxes less subsidies.

2.2.3 The literature on social rates of return from innovations.

20. Griliches' 1958 study of hybrid corn demonstrated that the social rate of return from R&D into the development of hybrid corn was around 35%, compared to a cost of financing of around 10%. This "social rate of return" is the interest rate that just equates the net present value of societal benefits from the R&D investment to zero (i.e., it is an internal rate of return). The comparison of social to private rates of return suggests a ratio of 3.5 times. Mansfield's 1977 study of 17 industrial innovations found a median private return of 25% against a median social return of 56%. Bresnahan's 1986 study of the impact of mainframe computers in financial services estimated that the (cumulative) downstream benefit of improvements in computers between 1958 and 1972 was between around five times the expenditure on computers in 1972. Trajtenberg's 1989 study of CT scanners find a capitalized benefit to cost ratio of 270%. Other studies use a variety of econometric approaches to calculate the extent of R&D spillovers. Regardless of methodology used, at least for successful innovations, the literature clearly demonstrates very large social benefits and demonstrates that private benefits are but a small share of the social benefits.

2.2.4 Estimated consumer surplus from telecommunications technologies (broadband and mobile)

21. Hausman (1997) finds that the annual consumer surplus from mobile telecommunications is, under plausible estimates of demand elasticity, roughly equal to the annual revenues earned by the mobile telecommunications industry. This consumer surplus estimate captures simply the consumer convenience value of mobile telecommunications, which at the time was mainly a consumer-facing "convenience" technology. Likewise, Dutz, Orszag and Willig (2008) find that broadband generated around $32 billion in annual consumer surplus in 2008, as against broadband subscriber revenues of **[[$20-$22 billion]]**. Of course, as mobile and broadband technologies have become key "platforms" around which innovation occurs, the value of these platforms to consumers has risen substantially. This implies a sharp increase in consumer surplus, if (as seems likely) a substantial portion of this increased value cannot be captured by service providers in the prices that they charge for subscriptions.

22. These empirical estimates inform our review of the IHS study. The IHS study differs from the reviewed empirical studies discussed above in one crucial dimension: 5G is a technology that is under development and has not been implemented. Empirical studies of the impact of ICTs, railroads and numerous other technologies benefit from the hindsight that historical data provides. Given the absence of any data on economic performance, innovation or consumer demand in the presence of 5G, the study is best evaluated in its proper context—the likely impact of a significant communications technology (perhaps ascending to GPT status) over a period of time. The literature is highly informative in this regard.

2.3 GPTs: Social and Private Returns and the Appropriability Problem

23. The large economic benefits from GPTs do, however, create a policy dilemma. The literature on GPTs in recent years highlights two central problems that could cause under-investment (relative to the level that is optimal from society's perspective) in GPTs. Bresnahan and Trajtenberg (1995) describes two of these problems:

> *GPTs introduce two-types of externalities: one between the GPT and the application sectors; another across the application sectors. The former stems from the difficulties that a GPT*

> *inventor may have in appropriating the fruits of her invention. When institutional conditions prevent full appropriation, the GPT is effectively underpriced and therefore, undersupplied. The latter stems from the fact that, since the application sectors are not coordinated, each one conditions its expansion on the available general-purpose technology. But if they coordinated a joint expansion, they would raise the profitability of the GPT and encourage its improvement. A better GPT benefits them all.*

24. The (related) literature on the economics of innovation has long recognized that social rates of return from innovations greatly exceed the private rate of return. This recognition—starting with Griliches'(1958) pioneering study of the social rates of return from hybrid corn and Mansfield's (1977) examination of the social rates of return from 17 innovations—reflects the policy rationale for intellectual property protection. Since it is inherently hard to exclude others from accessing knowledge—e.g., how to implement a particular protocol in a wireless communications system—many inventions could easily be copied and appropriated by others. This obviously provides a dis-incentive for would-be inventors. But given that social returns are potentially much larger than private returns even in the presence of strong intellectual property rights, a lack of innovation due to the absence of strong intellectual property protection implies large reductions in social welfare.

25. Teece (2017) further points out that even strong patent rights rarely translate into strong appropriability for the inventor. First, upstream firms—inventors—may find that the successful commercialization of a product requires the participation of both downstream firms, and in some cases, complementary upstream firms. Upstream firms sometimes have the option to vertically integrate downstream, and doing so can increase the appropriability of an invention. But, in practice, the upstream firm may find that the value of a core technology is enhanced when there are competing downstream firms vying to develop "complements" that increase the value of the core technology itself. This is intuitively easily understood with reference to the example of hardware and software, where the hardware serves as a platform around which (or upon which) innovation occurs. In some cases, vertical integration may be the appropriate way to internalize "complementary efficiencies" but in other cases, it may not be. Practical and organizational difficulties may also prevent successful vertical integration—the managers of a specialized technology firm may find running a manufacturing operation a rather difficult task, for example. These considerations likely explain why inventors license out their inventions. The difficulties of finding "vertical instruments" (e.g., contractual restraints such as exclusivity, the right pricing structure) short of outright (and infeasible) vertical integration may also explain, in part, why firms continue to license even though the returns from licensing constitute only a small share of the overall surplus from the invention.

26. In any case, even if sufficient vertical instruments could be found to solve vertical contracting issues, in many settings, maximizing the social returns from a technology may depend upon complementary innovation at the same horizontal level. For instance, in the context of technology contributed to a standard, the success of any one technology may depend on the success of the overall standard, which may consist of many scores of individual technologies. This too may lead individual technology inventors to under-invest in technologies that are designed for inclusion in a standard, a situation that the now-familiar focus on the market power allegedly conferred by standards substantially exacerbates. These problems become especially acute, as also noted in the extract from Trajtenberg above, in the case of a GPT—the pervasiveness of a GPT means that the "externalities" from a GPT encompass a vast range

of economic actors, making it inherently very difficult to align private and social incentives through (for example) some corrective mechanism, whether it be voluntary vertical integration or some facet of public policy. As we discuss subsequently, there are crucial ways in which public policy can impact upon the estimated gains from 5G broadband deployment that IHS estimates. We continue, however, by reviewing IHS' key empirical findings.

3 Review of IHS Study

3.1 Is "5G as GPT" a Reasonable Story?

3.1.1 Mobile Broadband: Not quite a GPT

27. IHS take the position that to date mobile technology and mobile broadband technology have not been truly central in the economy. This position requires some qualification and explanation. In developing economies at least, mobile telecommunications have at a minimum being a very significant enabling technology with a large macroeconomic impact. Jensen's 2007 study of the impact of mobile telecommunications on the fishing economy in Kerala, India, clearly demonstrates the efficiencies associated with even relatively simple mobile technology: it reduces search costs and inefficiencies associated with a lack of information about demand and supply conditions in different markets. Mobile technology has also served as a platform for banking and financial services in developing markets. In developed markets, mobile broadband has also arguably facilitated innovation in the smartphone ecosystem, although the roles of the device itself and of fixed-line networks are also critical. IHS acknowledges the important role that mobile broadband has played in some settings, of course, but points out that in business and industrial settings, mobile broadband has not yet been transformative. The problems of contention and latency, problems with siting and in-building penetration, and lack of available spectrum are among the factors that have made mobile broadband a backstop or complement to fixed broadband in countries with well-developed fixed broadband networks.

3.1.2 5G and the transition to "true GPT" status

28. Mobile broadband has also been subject to rapid improvement. Crucially, mobile broadband is cheaper to deploy in the "last mile" than is fixed broadband. If mobile broadband networks are able to surpass the performance of existing fixed-line networks in the 5G era, bandwidth requirements (even of intensive business users) may be more easily and cheaply met through mobile broadband networks. The alternative of next-generation fixed networks has been patchily deployed to date, its deployment in Europe and North America retarded by investors' fears over their ability to recover on large, sunk investments in such networks. Mobile networks have generally been competitively supplied, whereas the legacy of monopoly provision of fixed telephony has created (in many countries) a regulatory regime that itself is the source of substantial investor uncertainty.

29. Especially in developing countries and in mid-density and low-density suburban and rural locations in the developed world, 5G mobile broadband may more cost-effectively meet the connectivity needs of businesses and industries than fixed broadband could. The case for

mobile broadband networks becomes stronger when one recognizes that the limiting factor on fixed broadband deployment is not technological progress, but rather the cost (direct and indirect) of civil and engineering works. In some settings, such as remote monitoring of agricultural sites, using fixed broadband networks will not even be an option.

30. More generally, if mobile technology can offer similar performance, it ought to be preferred to fixed technology, especially in applications that depend on connecting up a large number of dispersed users. In the context that IHS cites, the "Massive Internet of Things", the probability that 5G mobile technology becomes the fulcrum supporting the extensive interconnectivity of devices and machines seems very reasonable. The same seems true for "Mission critical" services that depend or are substantially improved by ubiquitous connectivity. Wireless technology is already preferred for relatively modest bandwidth applications such as smart metres. As the technology continues to improve, there will be a "social saving" that can be had from the avoided cost of deploying fixed broadband networks. 5G will also benefit from the fact that much invention that will ultimately complement 5G is already underway—e.g., developments in artificial intelligence (AI) and machine learning (ML). The harnessing of truly ubiquitous broadband on a global scale (enabled by 5G technology) with developments in computing such as AI and ML offers a prospect similar to that experienced by the marriage of computing and telecommunications networks in the late 1990s.

31. Thus the overall contention that mobile broadband will become the "glue" supporting the connected global economy of the future seems quite reasonable, given the advantage of flexibility and ubiquity that mobile broadband possesses. The GPT literature is thus the appropriate "lens" through which to evaluate the potential impact of 5G, and it is this "lens" that we use to review the quantitative claims of the IHS study.

3.2 IHS' Empirical Estimates in Context

32. IHS' estimates suggest that 5G will drive an average of 0.2% a year of additional GDP growth between 2020 and 2030. They project GDP growth of around 2.9% annually during this same time period. Thus during the ramp-up of 5G (when R&D and initial capital expenditures by network operators are underway) roughly some 7% of growth will be powered by 5G. Given the estimates of Roller and Waverman regarding fixed line deployment in the 1970-1990 time period, and the findings of growth accounting studies regarding the contribution of ICT (perhaps as much as 50% of U.S. growth, or 2% a year), this number is apparently very conservative. However, those other studies may have been capturing growth in a period in which the relevant technologies were already widely diffused and moving or even achieving universal adoption. IHS' estimates are actually quite close to the estimates for the contribution of communications hardware and communications sector TFP to U.S. productivity growth in the 1990s—for example, Oliner et al. (2007) attribute 8% of labour productivity growth in the 1995-2000 period to a combination of increased telecom equipment investment and TFP improvements in the telecom equipment sector. IHS' estimates are also close to the estimates obtained by Chalmers Institute of Technology (2012) related to the economic impact of a doubling of broadband speeds (0.3% per year), and well above the recent estimates of the increase in GVA as a result of increased broadband speeds between 2013 and 2024 in the UK (0.07% per year).

33. IHS further estimates that the Net Present Value (NPV) of the gains in GDP between 2020 and 2035 would be $2.1 Trillion. To contextualize this number, we looked at plausible estimates of the social rate of return derived from econometric studies of the impact fixed-line telephony. These estimates are typically between 30% and 60% (per year). The private cost of capital for telecommunications firms is typically between 10% and 15%. As demonstrated in Appendix A, the ratio of the social rate of return to the private cost of capital yields a multiplier that can be applied to the net present value of the investment cash flows. Based on IHS' estimates of capital expenditure between 2020 and 2030, and a cost of capital of 12%, the NPV of the estimated global cap-ex is around **[$775 billion]].** Assuming a social rate of return of 35% (at the mid-point of estimates in Appendix B), we obtain a multiplier that is equal to 3.33. Further adjusting this multiplier to account for an asset life of 15 years, we obtain an NPV of the social returns from the investment that is equal to **[[$1.89 Trillion]]**. This **[[$1.89 Trillion]]** can be thought of as representing the lump-sum equivalent of the future gains from 5G if 5G had roughly the same impact as fixed-line telephony in the 1970s and 1980s. This compares against the $2.1 Trillion that IHS estimates, which is the lump-sum equivalent of the future income gains from 5G as estimated in IHS' model, from 2020 to 2035. Thus the IHS estimates are consistent with a conservative and reasonable assumption of the social rate of return from 5G investment of somewhat less than 35%. [[**←Can we get cap-ex data to 2035 to make the comparison more precise**]].[6]

3.2.1 The "ecosystem" perspective

34. Looking beyond the classic GPT perspective, the notion of "ecosystems"—software, devices and content—that are focused around mobile platforms has become a familiar one. IHS provide estimates of the 5G value chain in 2035. These estimates take into account that increased spending by the economic sectors supplying the components of the 5G value chain has a ripple effect on the aggregate economy. Specifically, the 5G value chain includes mobile network operators, core technology providers, OEM device manufacturers, mobile site operators and manufacturers of mobile network equipment. Increases in R&D and capital expenditures by these economic actors translate into an increase in the size of these economic sectors, which in turn translates into increased demand experienced by other parts of the economy that supply these 5G-linked economic sectors. IHS estimates that this 5G value chain effect will be worth $3.5 trillion in 2035 and will support 22m jobs. These estimates are arrived at using Input-Output tables and do not capture the productivity benefits or economic transformations from 5G. Instead, the estimates provide a static snapshot of the size of the ecosystem in 2035. This estimated ecosystem size compares with a previous estimate (in constant, comparable dollars) of $3.1T for the *entire mobile value chain* in 2014. The greater expected pervasiveness of 5G in the industrial economy suggests that the ecosystem around it should be larger than the ecosystem around current mobile technology, even if one looked just at the portion of the mobile ecosystem that was specifically linked to 5G.

35. [[**Consider shedding this discussion as it is difficult to find an appropriate comparator for this piece of the analysis→**]] Finally, IHS also estimate the size of the 5G-enabled

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[6] This multiplier is applied only to capital investment. It is not applied to R&D spending. One concern with applying to it both R&D spending and capital investment is that the benefits of the R&D may be largely embodied in the capital equipment that is deployed by the communications industry.

economy. This is estimated at $12 Trillion in output in 2035. Care should be taken to recognize that the "output" reported is effectively just a summation of the "enabled" sales -- sales increases that are specifically enabled by 5G as opposed to previous waves of mobile technology. It is not the same thing as GDP, since GDP is based upon "gross value added" (i.e., taking into account the value of intermediate consumption). This analysis is based upon an application of detailed use cases to each of 16 sectors. It can be reasonably viewed as a "bottom-up" perspective on the diffusion level and maturity of 5G use within each of these sectors. Further, since the sales increases are summed up only for a subset of industries (for which it was possible to devise use cases), it is a lower bound estimate of the extent to which 5G fuels the aggregate economy in 2035. The detailed used cases developed for each of the 16 sectors translate into an economic impact on these sectors, and given the weight of the studied sectors in the aggregate economy, translate into a sizeable impact for the aggregate economy as a whole. Thus the "bottom up" approach supports the contention of "5G pervasiveness", which is consistent with the GPT-like potential of 5G. Clearly, given the lack of available data about 5G this calculation is necessarily a best estimate rather than a precise prediction.

36. Given the stock of knowledge we have about the impact of GPTs, or even just the impact of previous waves of telecommunications technologies, the estimated impacts of 5G seem reasonable. 5G is expected to (via its direct and indirect effects) account for less than 10% of world growth in the 2020-2035 period. At its peak, the ICT sector accounted for between a quarter and a half of (very high) U.S. growth in the late 1990s. 5G technology will not, of course, match the impact that the entire ICT sector has achieved, but the projection that its impact may be a significant fraction of the impact achieved by ICT seems reasonable. Of course, the size of that impact is significantly mediated by policy factors. There are two public policy factors that we discuss below: (a) policy towards intellectual property rights which could impact on the level of investment in fundamental technology research, and (b) regulatory barriers that slow down deployment of networks.

4 The Important Policy Implications

37. The economics of innovation and the literature on GPTs both suggest that large social gains dwarf the returns to investors. Additionally, since the impact of GPTs depends on complementary investments by both vertical and horizontal complement producers issues of appropriability loom large, with implications for incentives to innovate, to license, to deploy different governance mechanisms for vertical relations between upstream and downstream firms, and to participate in standards-setting.

38. The IHS results suggest the potential for substantial economic gains from deployment of 5G technology. But this potential could be vitiated by poor public policy choices. Public policy has to recognize that the fundamental problem associated with innovation may be that the innovator has too little incentive to invest, or will tend to invest too little, relative to society's incentives for the investment to take place. As Teece (2016) points out even strong patent protection offers only some level of "appropriability" for the inventor. In many circumstances, licensing rather than vertical integration and/or exclusivity may be the most feasible way to monetize the value of an innovation. Some firms will lack the access to capital or the know-how to implement or commercialize a fundamental technology. In other cases,

complementary innovation may be more effectively unleashed and its value more effectively monetized by competition between several licensees to find commercial uses for the innovation. The need to incentivize complementary innovation by implementers may, however, constrain the level of license fees. As an empirical matter, it has been recognized that licensing revenues are typically quite modest in relation to the value of the product (Arrow (1962) and Arrow (2012)).

39. The ability to derive commercial value from an invention may further depend on the success and quality of complementary inventions. This is the case in standards-driven environments such as mobile communications technology. As with vertical complements, ownership of horizontal complements aids "appropriability" (Teece (2016)). But there is also the risk that the value of an invention may instead be appropriated by those who control complementary assets.

40. In the context of standards-driven mobile technologies, antitrust authorities have dwelt on the potential for standardization to confer market power on the owners of standards-essential IP. Various proposals to cap or curb royalty rates—ranging from aggregate caps to determining (fancifully) a royalty rate based on a technology's value contribution relative to pre-standardization alternatives—have emerged as a response to this concern about market power. But any attempt to limit IP owners to a "fair" reward may instead simply discourage innovation. Technology developers bear the risk of unsuccessful technologies (e.g., those that do not make it into the standard) and unsuccessful R&D investments. If the rewards available for a successful technology are "capped", then barring the very unlikely situation in which a cap can compensate them for the risks they undertake in the first place, it is likely that investors in fundamental technology will have diminished incentives to invest.[7] This will likely only exacerbate the appropriability conundrums that Teece (2016) highlights. The wedge between the inventor's incentive to undertake the necessary effort to develop a technology and society's incentives to develop the technology will only widen. The policy emphasis on ensuring that upstream technology licensors do not get "too much" of the social surplus from technology use seems misplaced from a conceptual and theoretical perspective.

41. The emphasis seems even odder given the lack of evidence that IP owners get "too much" of the reward from mobile technology usage. If this were the case, it is surprising that one observes such a dynamic and continually innovative market. Indeed antitrust policy that over-emphasizes the risks of licensor market power and under-recognizes the many ways in which investment incentives need to be strengthened rather than weakened threatens the development of an even more dynamic and innovative market in the 5G era.

42. Equally, restrictions or presumptions against particular type business models may be unwarranted. One should not be surprised to see that firms will experiment with different vertical and contracting structures as they attempt to create the right incentive and risk-sharing structures. Thus some firm may decide on a technology licensing model. Others may find vertical integration more feasible and attractive. In other circumstances, vertical controls such

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[7] Implementers do have the option to not invest in standards-compliant products until the standard is developed and in many cases until at least some evidence of its viability and success is available. For example, Apple did not start manufacturing the iPhone until well after the UMTS standard was developed and other parties had launched products incorporating the standard. In this sense, there is an argument that the implementer benefits from the unpriced option to "wait and see", and in fact that this option should be priced.

as exclusivity between handset manufacturers and network operators may help to develop demand for products that showcase the capabilities of the new technology or standard. This was the case with the initial exclusivity for the iPhone, which ushered in the smartphone era and spurred wider and more aggressive deployment of 3G mobile technology. Policy restrictions—such as laws against exclusivity or efforts to exclude or disadvantage unintegrated technology licensors—would again threaten investment in 5G technology and the successful development of an eco-system around it.

43. Finally, although 5G may have the ability to operate in both licensed and unlicensed spectrum band, if successful deployment of 5G requires licensed spectrum, then government policy towards spectrum licensing needs to incorporate the GPT-like nature of 5G into its reasoning. Across the world, but most particularly in developing countries, spectrum licensing has been seen too much in terms of its revenue-generating potential and too little in terms of the social surplus derived from providing the spectrum to mobile operators, rather than keeping it in some other use. Policies that have deliberately restricted spectrum availability (so as to increase its scarcity value) have retarded mobile broadband deployment in some countries. A failure to recognize that the provision of mobile broadband demands scale and cannot be done by dozens of sub-scale operators has been a problem in some developing country markets: too little spectrum is available to effectively deploy mobile broadband networks and operators have lacked the scale to fund subsequent investments. The advent of 5G—which has more potential to be a GPT with uniformly large effects throughout the world than did fixed broadband and other ICTs—offers an opportunity for new policies that reflect the learnings of the literature on GPTs and innovation.

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[[Endnotes to be completed]]

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Table 1: Evidence on the Value of GPTs, Successful Innovations and Telecoms and Broadband Diffusion

Theme	Key Studies and Findings	Comments
Social savings from historic GPTs	Cliometric studies. Classic examples include railways and steam engines in the 19th century. Crafts (2003) reports that steam power contributed a social savings of 0.2 percent of British GDP in 1760 to 1800, and 1.8 percent of British GDP in 1870-1910. Social savings from freight railroads estimated at 4% (roughly) of GDP in England and Wales in 1859; rising to 10% by 1890. Estimates of social savings as high as 31% of GDP in Mexico in 1910. See Crafts (2004).	Literature finds a very long time lag between technology development and strong productivity gains for "historic" GPTs. Big boosts to growth happened some 40 years after the emergence of electricity and perhaps 80 years after James Watts' steam engine
Growth Accounting Studies of GPTs, predominantly ICTs.	ICT capital deepening and ICT-induced TFP growth may have accounted for as much as 50% of U.S. GDP growth (Jorgeson and Vu (2016)). The contribution of communications hardware and TFP growth in the hardware-producing sector-- the "C" in "ICT"-- may have been around 8% of total productivity growth in 1995-2000. Retrospective studies (Crafts (2003)) suggest that the impact of ICT was both significanly larger than and more immediately experienced than the impact of electricity, steam and railroads.	Major shortcoming of growth accounting studies is that they do not correctly measure the proportion of TFP growth in ICT-using industries that is due to ICT-related organizational changes. They also do not account for the interaction between "I" (computing, data storage) and "C" (telecoms and data transmission). Thus the potential share of "C" could be understated.
Studies of successful innovations	Griliches finds a social rate of return of 35% to 40%, compared to a private cost of capital of 10%. Studies of agricultural R&D find social rates of return as high as 100%. Mansfield et al. (1977) find median social rate of return of 56% against private rate of return of 25% for 17 successful innovations. Bresnahan (1986) finds that the spill over (consumer surplus) to users in the financial services sector from mainframe computers between 1958-72 was at least five times their expenditure in 1972. Trajtenberg (1989) finds similarly large benefits for CT scanners.	The literature suggests consistently finds social rates of return are much greater than private rates of returns for successful innovations.
Econometric estimates of the impact of telecom and broadband diffusion	Roller and Waverman (2001) find that the spread of fixed lines explains a very high share of OECD-area economic growth between 1970 and 1990-- maybe as much as a third of GDP growth in Germany. World Bank (2009) finds that 10 additional broadband lines per 100 persons increases GDP growth by between 1.21 and 1.38 percentage points per year. Chalmers University of Technology (2012) finds that doubling broadband speeds adds 0.3 percentage points per year to GDP growth. SQW and Cambridge Econometrics (2013) find that expected improvements in broadband between 2013 and 2024 will contribute around 0.07 percentage points per year to the growth rate of Gross Value Added in Britain.	This literature produces higher estimates of the contribution of telecoms and ICT because it attempts to account for spillover effects which the growth accounting methodology cannot adequately address.

Appendix A: Derivation of a Multiplier for Telecommunications

1. As a practical matter, the total economic return (i.e., the sum of all returns to all social actors) may be calculated as a multiple of the investment cost, using what is known as the total economic returns multiplier. It can be shown that the multiplier is effectively the ratio of the total economic rate of return to the discount rate (cost of capital). An adjustment may be necessary for the period over which the total economic return and private returns are evaluated. The investment cost is the net present value (NPV) of the investment cash flows discounted using the discount rate, similarly for the total economic returns. Figures may also be discounted to the valuation date using the discount rate.

Total economic return: net flow per period : $RT = \rho I$

Where: I = NPV of investment cash flows.

Total economic return: net present value (stock): $R = \int_0^N \rho I_t .e^{-rt} .dt$

Notation: m_N = Total return multiplier (which depends on the value of N, the number of years over which the returns are evaluated)

For large N, the total economic return equals approximately $I(\rho/r) = I.m$, where the total economic return multiplier $m = (\rho/r)$.

For small N the adjusted total economic return multiplier m_N is used.

$$\int_0^N \rho I_t .e^{-rt} .dt = I(\rho/r).[-e^{-rt}]_0^N = I(\rho/r).(1-e^{-rN})$$

$$= I(\rho/r).\ m_N$$

Where: $m_N = 1-e^{-rN}$

Total economic return $= I(\rho/r)$ for $N = \infty$

$= I(\rho/r).(0.97)$ for $N = 20$; $r = 14.7\%$

$= I(\rho/r).(0.82)$ for $N = 10$; $r = 14.7\%$

$= I(\rho/r).(0.58)$ for $N = 5$; $r = 14.7\%$

2. From an economic standpoint, what is being done here is that the basic multiplier formula used [namely, $I(\rho/r)$] is strictly correct only for projects that generate a stream of benefits indefinitely into the future. For projects that generate a stream of benefits only for a limited time period, it is necessary to adjust the basic multiplier downward to reflect the fact that the benefits do not last indefinitely. Mathematically, this is most readily done with a numerical adjustment to the basic multiplier, as shown above.