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Bridging the Mobile Digital Divide in Sub-Saharan Africa:  
Costing under Demographic Change and Urbanization

by C. Emre Alper and Michal Miktus

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I N T E R N A T I O N A L M O N E T A R Y F U N D

**IMF Working Paper**

African Department

**Bridging the Mobile Digital Divide in Sub-Saharan Africa  
Costing under Demographic Change and Urbanization<sup>1</sup>****Prepared by C. Emre Alper and Michal Miktus**

Authorized for distribution by Benedict Clements

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**Abstract**

Digital connectivity, including through the modern cellular network technologies, is expected to play a key role for the Future of Work in sub-Saharan Africa (SSA). We estimate the cost of introducing a full-scale 4G network by 2025 in SSA and an operable 5G network by 2040. We adapt the costing model of Lombardo (2019) by accounting for the significant demographic transformation and rapid urbanization in SSA. We use the WorldPop and GADM databases and the UN's medium-variant population projections to project the population densities at the highest level of administrative division for each SSA country in 2025 and 2040. For full 4G connectivity, the required capital and operational costs stands approximately at US\$14 billion by 2025 and for 5G connectivity, costs amount to US\$57 billion in 2040, conditional on having the 4G in place by 2025. These costs roughly translate to 8.4 percent of annual subscriber income, on a median basis, by 2025 for 4G and 4.9 percent of subscriber income by 2040 for 5G. Having the infrastructure in place is not sufficient to bridge the mobile Digital Divide. In addition, policies are needed to address affordability and knowledge gaps.

JEL Classification Numbers: O33, J11

Keywords: Digitalization, 5G cellular network, Demographics, Urbanization

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## I. INTRODUCTION

**1. Improving of digital connectivity is emerging as a crucial policy area in the context of demographic expansion and rapid urbanization in SSA.** To create a sufficient number of jobs for its booming population, SSA has to fully exploit the opportunities from the Fourth Industrial Revolution, by bridging what has been termed the *global Digital Divide*.<sup>2</sup> Empirical evidence suggests that if there is an adequate digital infrastructure and a supportive business environment, new forms of business will flourish, providing employment opportunities for the educated as well as the less educated.<sup>3</sup> At the same time, changes in technology—along with climate change and global economic integration—will have an important bearing on growth and employment (IMF, 2018). In this light, improving digital connectivity, including its mobile component, is a key policy area to promote job creation and improve growth outcomes.

**2. 4G and 5G technologies are revolutionary in terms of creating new economic and social opportunities.** Along with Artificial Intelligence, the advance of 4G and 5G is regarded as a field of innovation, enabling smarter societies (International Telecommunication Union (ITU), 2018). The introduction of Fifth Generation networks is expected to supercharge wireless speeds, power a surge in the Internet of Things (IoT) and usher in a new area of technological capacities. Harnessing the potential of technology and the data economy could help support meeting the UN's Sustainable Development Goals in Africa, from assisting development and accelerating prosperity to ending poverty. By supporting advanced protocols, new users, modern devices, and novel applications, it further promises an open platform for information sharing to anyone and anything, anytime and anywhere (El Hattachi and Erfanian, 2015). Moreover, 4G and 5G are expected to serve to bridge the Digital Divide, with smartphones serving as a leapfrog technology to connect with the online world.

**3. Policy action is needed to reap the benefits from 5G technology to achieve higher productivity and inclusive growth.** Due to high upfront costs and relatively poor returns on investment, private mobile telecommunications operators frequently lack the financial incentives to operate in sparsely populated areas where broadband infrastructure is not in place. In the absence of any government policy action, only urban areas may be upgraded to new technologies, resulting in a plethora of underserved areas with low connectivity, inferior quality of service, and higher prices. Hence, widespread implementation of 4G and 5G cellular networks requires collaboration between the public and private sectors and an updated Technological Infrastructure Policy. Moreover, the benefits of 5G adoption can be expanded by appropriate actions to endow the poor with smartphones in rural and undeveloped areas of SSA and by reconsidering the taxation of mobile phone-based transactions which currently slows the pace of the ongoing mobile revolution in SSA (Ndung'u, 2019).

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<sup>2</sup> The term Digital Divide or digital split owes to Norris (2001).

<sup>3</sup> Among others, see Hjort and Poulsen (2019).

**4. Apart from infrastructure gaps, affordability and user knowledge also contribute to the current mobile Digital Divide.** Even if the required 5G infrastructure is made available, uneven access to modern mobile technology adoption may persist if poorer and rural households cannot afford *smart* devices and monthly data fees or if they lack the capacity to access the internet due to insufficient education or skills. Low income per capita combined with inadequate human capital will stifle the demand for 5G technologies, especially in rural areas, reinforcing the mobile Digital Divide. This issue, while important, is outside the scope of the present paper, which focuses on the cost (to either the private or public sector) to provide the necessary infrastructure to bridge the mobile Digital Divide.

**5. Experience from 5G forerunners provides a valuable framework for developing a costing framework for SSA.** The Fifth Generation is becoming a global standard and the experiences from early adopters like the South Korea, China, or the United States may be useful to help assess the implementation costs in SSA. At the same time, the SSA countries face their own unique challenges including the increasing population in the next two decades, accompanied by rapid urbanization. These also will need to be taken into account in factoring in the likely costs of providing 4G and 5G in the region.

**6. A pronounced increase in population and a rapid expansion in the labor force characterize the current demographic trends in SSA.** Specifically, SSA population is projected to rise to 1.7 billion in 2040 from 1 billion today, while the labor force will increase by 20 million per year over the next two decades (IMF, 2018). The expected rise in population constitutes an opportunity to seize a demographic dividend, while simultaneously requiring an improved connectivity. Governments should consider infrastructure gaps, with an emphasis on digital, to leverage the opportunities from the ongoing technological revolution.

**7. SSA is also experiencing rapid urbanization and the associated challenges.** The urban population has on average risen by approximately 4.4 percent annually over the last 50 years, with the average urbanization rate now exceeding 40 percent (United Nations, 2018). Moreover, urban population is expected to double over the next 25 years with higher migration to cities from rural areas (United Nations, 2017). Urban centers in general play a crucial role in combatting poverty and sustaining economic growth. Yet, African cities share in general three challenges that need to be addressed to support high and inclusive growth: they are crowded, but not economically dense; disconnected; and costly for households and firms (Lall and others, 2017).

**8. This paper aims to estimate the cost of introducing a full-scale 4G network by 2025 in SSA and an operable 5G network by 2040.** First, we briefly describe the evolution of modern cellular technologies with a specific focus on 5G. While there is no consensus on technology requirements of the Fifth-Generation cellular networks, we enumerate its agreed use cases, including the need to satisfy the heterogeneous networks and device-to-device communication. We next investigate the current state of play in mobile digital connectivity in SSA based on the average monthly mobile data consumption per person and note the existence

of significant global mobile Digital Divide. We then outline the costing framework for both 4G and 5G adoption in SSA. Specifically, we follow the methodology developed by Lombardo (2019) of the European Broadcasting Union which assumes a non-standalone network architecture.<sup>4</sup> It is based on a synthetic country, the average of France, Germany, Italy, Spain, and United Kingdom, but we adjust the framework by accounting for SSA-specific characteristics.

**9. Our central contribution lies in accounting for SSA characteristics.** Specifically, we account for demographic transitions, rapid urbanization including by projecting population densities for highly decentralized administrative areas. We investigate trends in population densities in highly decentralized administrative areas in each SSA country from 2000 to 2020. We then use them along with the United Nation’s medium-variant population projections to infer the population densities for 2025 and 2040 for each SSA country. They are then used to determine the required mobile digital infrastructure cost and the associated operational expenditures of implementing full 4G by 2025 and operable 5G by 2040. In the costing methodology we also account for heterogeneity in the cost of electricity, current 4G coverage and the number of licensed mobile operators in each country, as well as the potential lack of fiber backbones.

**10. We find that overall costs to implement full 4G in SSA by 2025 would stand at US\$14 billion and, conditional on that, an operable 5G by 2040 would cost an additional US\$57 billion.** In annual terms, the required capital and operational costs would stand at US\$2.5 billion (0.04 percent of 2025 SSA GDP) and US\$3.9 billion (0.03 percent of 2040 SSA GDP) for full 4G and operable 5G, respectively. These roughly translate to 8.4 percent of income per subscriber for 4G connectivity in 2025 and 4.9 percent of income per subscriber for 5G connectivity in 2040. We decompose annual overall costs into capital spending and operational spending components: to achieve the full 4G connectivity by 2025, capital expenditure spending would reach approximately US\$2.1 billion and the accompanying operational expenditure spending would be US\$0.4 billion. Annual costs for 5G connectivity in 2040 would be US\$3.3 billion and US\$0.6 billion, respectively, for capital and operational expenditures in SSA. We also report significant heterogeneity in costs to implement 4G and 5G per subscriber income across SSA countries reflecting largely the differences in current state of play in mobile infrastructure as well as differences in population growth, urbanization rates, and real GDP growth projections.

**11. The structure of the paper is as follows.** Section II briefly describes the evolution of mobile networks and finally illustrates the global mobile Digital Divide. Section III introduces the costing methodology, extensively describing the underlying assumptions and illustrating the framework to address the demographic transition and rapid urbanization to project population densities in next two decades years. Section IV presents the costs of ensuring the

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<sup>4</sup> Non-standalone approach means that mobile operators can use the existing sites/infrastructure and 4G spectrum as an anchor connection with a densified network of small cells and higher-band spectrum. It would facilitate high-speed data services requirement of both 4G and 5G.

required infrastructure for full coverage of 4G SSA in 2025, and conditional on that, cost of implementing operable 5G by 2040. Section V concludes.

## II. CELLULAR NETWORKS

**12. In this section we focus on modern mobile technologies, including their potential impact on bridging the mobile Digital Divide.** We start with a brief description of the evolution of cellular networks, starting from the First Generation to the currently evolving definition of the Fifth Generation. We illustrate the mobile Digital Divide from a global map of the monthly mobile data consumption per capita in each country. Finally, we characterize the fundamental economic and business-related aspects of introducing 5G technology, as well as implications for bridging the mobile Digital Divide.

### A. EVOLUTION OF MOBILE TECHNOLOGY

**13. The First Generation of cellular networks was designated uniquely for voice applications (Figure 1).** 1G was first introduced in Japan in 1979 by Nippon Telephone and Telegraph and followed by Europe and the United States a few years later (Sharma, 2013), 1G technology consisted of analogue systems employing frequency division multiple access for the voice call (Hossain, 2013). It was characterized by the indigent voice links, low capacity, total lack of security and unreliable handoff.<sup>5, 6</sup>

**14. The Second Generation of wireless mobile technology improved on 1G using digital signals to enhance transmission.** It was introduced in the early 1990s (Sharma, 2013) with the digital modulation schemes, not only improving voice service, but providing simultaneously text messaging (Nokia, 2014), broadly known as Short Message Service (SMS) and e-mail (Elmannai and Elleithy, 2014). Moreover, 2G enhanced the spectral efficiency and augmented the roaming level of development, allowing the creation of the global system of mobile communication (GSM) standard.<sup>7</sup> The so-called 2.5G launched the general packet radio service (GPRS), constituting a substantial step towards the implementation of 3G.

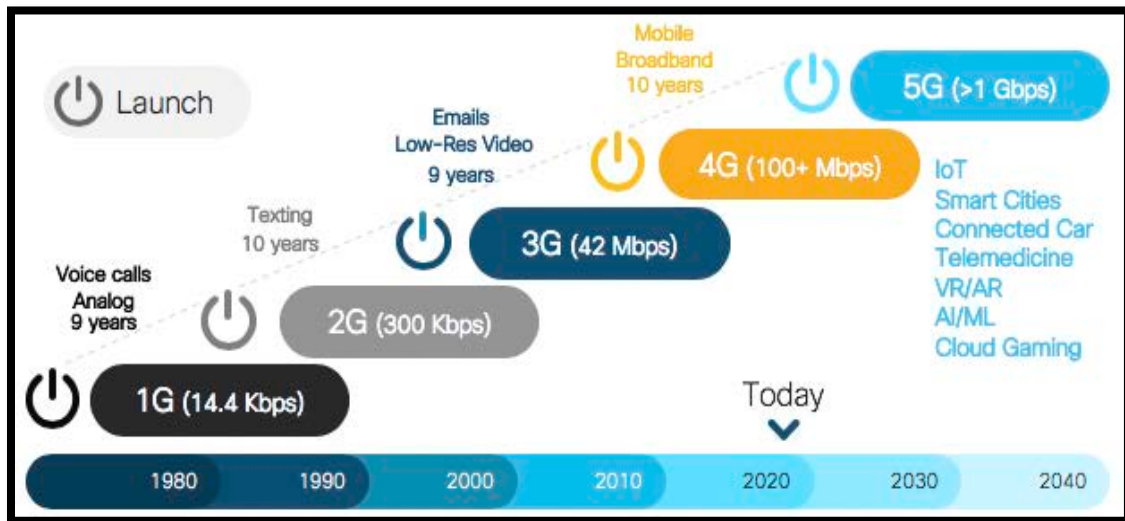
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<sup>5</sup> In the context of networks, capacity is the complex measurement of the maximum amount of data that may be transferred between network locations over a link or network path

<sup>6</sup> In a cellular telephone network, handoff is the transition for any given user of signal transmission from one base station to a geographically adjacent base station as the user moves around.

<sup>7</sup> In a cellular telephone network, spectrum efficiency equals the maximum number of users per cell that can be provided while maintaining an acceptable quality of service.

**Figure 1. Evolution of Mobile Technology**



Sources: Cisco Visual Networking (2019).

**15. The Third Generation of wireless cellular technology enabled mobile internet access.** Launched in 2001, 3G networks allowed for higher capacity for voice services in connection with the relatively fast and affordable mobile data services (Nokia, 2014). In other words, e-mail, wireless web base access, video and multimedia services were the flagship features offered by the Third-Generation cellular network technology (Elmannai and Elleithy, 2014). Continuous improvements in spectral efficiency lead to the broader network capacity and the Universal Mobile Telecommunication Service system, which enhanced the old GSM standard.

**16. The Fourth Generation of mobile networks allowed fast and secure data transfers.** 4G supports significantly higher capacity and both voice and data services. It involves a move from the operator-centric 3G concept—which emphasizes the importance of voice and messaging services—to the service-centric one, emphasizing data usage (Janevski, 2009).

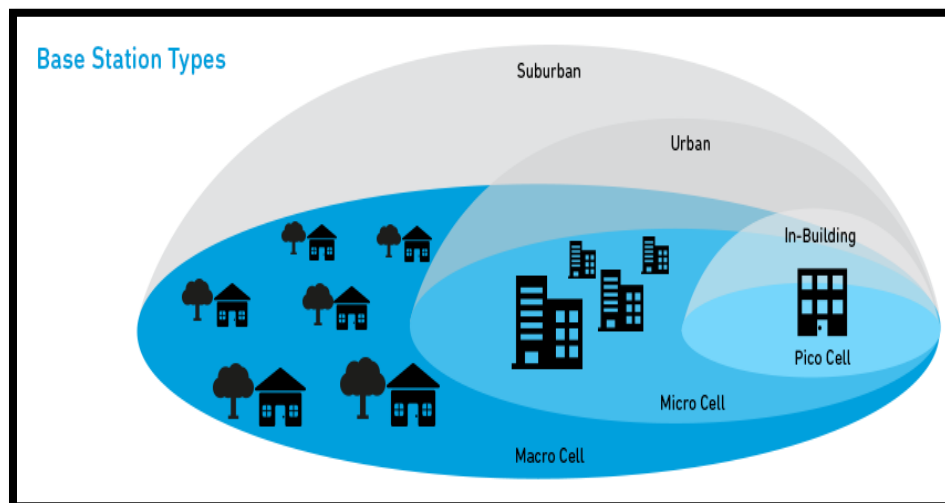
## **B. 5G NETWORK: DEFINITION IN PROGRESS**

**17. Fifth Generation is the latest iteration of cellular technology, designed to increase the speed and responsiveness of wireless networks substantially.** The precise definition of “5G” is evolving. According to one of the leading industry associations in this area, the 3<sup>rd</sup> Generation Partnership Project (3GPP, 2018), 5G can be defined as any system using the 5G NR (5G New Radio) software. Others view 5G as any cellular network system satisfying the requirements of the ITU (2015), published as the International Mobile Telecommunication 2020 standards (IMT-2020). Despite the lack of worldwide consensus on a precise definition, there is a general agreement that 5G technology would usher in new paradigms in connectivity in mobile broadband wireless systems.

**18. 5G networks meet broad criteria for speed, reliability, and latency.** 5G network speeds is expected to achieve a peak data rate of 20 gigabits per second for the downlink and 10 gigabits per second for the uplink (ITU, 2015). Moreover, the latency in a 5G network could fall under 4 milliseconds in a mobile scenario and up to 1 millisecond in Ultra Reliable Low Latency (that is, low time delay) Communication scenarios. It will permit Internet of Things and will have wide-ranging implications, including self-driving cars and what have been described as “smart-cities,” such as Seoul (South Korea) or Singapore. 5G networks are also expected to provide always-on capabilities and aim to be energy-efficient, by minimizing the power a modem consumes, based on the amount of ongoing traffic.<sup>8</sup> In addition to the advancements in higher speed, larger capacity, and lower latency, 5G offers network management features, such as network slicing, which authorizes mobile operators to construct multiple virtual networks within a single physical 5G network, potentially leading to World Wide Wireless Web.

**19. For the remainder of the paper, we will focus on heterogenous 5G networks that require concurrent operation of macro-, micro-, pico-cells.** Heterogenous networks are sometimes referred to as a non-standalone network architecture, which is a widely use technique to cope with increased mobile traffic demand Clerckx and Oestges (2013). They are created as the classical macro-cell network, overlaid with low power-nodes (micro- and pico-cells) deployed in the macro-cell area. Due to significantly lower range, micro- and pico-cells are typically used to extend coverage and capacity in areas difficult or expensive to reach using the more traditional macro-cell approach. Thus, they are mainly designed for indoor areas where outdoor signals do not reach well, or to add network capacity in areas with very dense phone usage, such as train stations or stadiums (Figure 2).

**Figure 2. Network Capacity Areas: Macro-, Micro-, and Pico-cells**



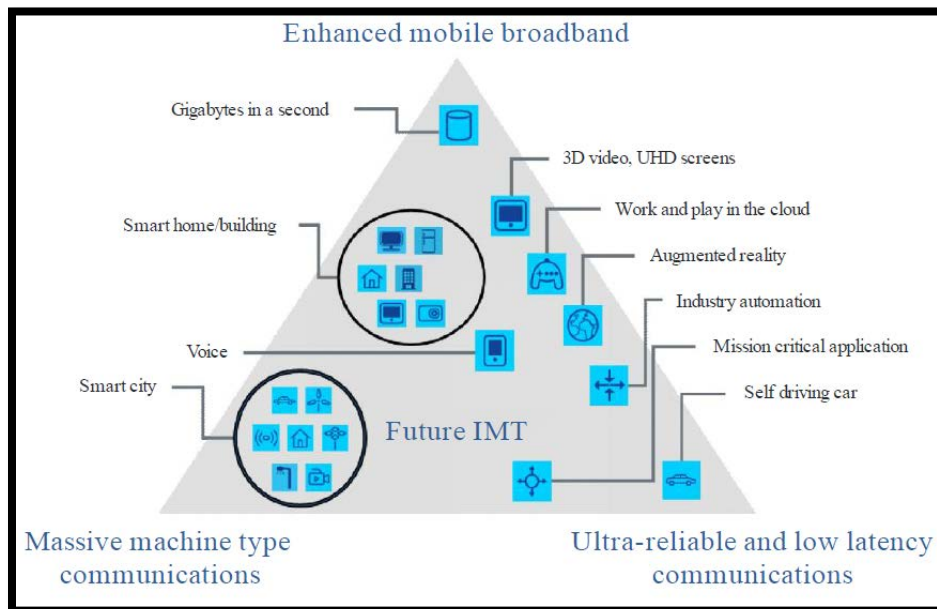
Sources: Qorvo, 2017.

<sup>8</sup> Internet of things denotes a network of connected things, including people, and in general the concept of connecting any device with an on and off switch to the Internet and/or to each other.



**20. There are three main 5G network use cases (ITU, 2018).** The first one, depicted in Figure 3, is the enhanced mobile broadband. This is expected to be the primary use case in the early developments of 5G networks (GSMA, 2018), delivering high-speed mobile broadband to high population density areas, aimed at the entertainment, video social networking and multimedia communications with higher resolutions video channels (EU, 2016). It would allow consumers to enjoy high-speed streaming on demand, while also permitting enterprise collaboration services to spread. The second use case is the enabling of massive machine-to-machine type communications, allowing a vast number of low-power, low-cost device connections with high scalability and increased battery lifetime, driving the evolution of smart cities and Internet of Things. It would ensure relatively cheap and universal connectivity with minimal energy consumption. The third and final use case is ultra-reliable and low-latency communications, sometimes referred to as critical machine-type communications, which are designed to use the network for mission-critical applications which demand stringent requirements for uninterrupted, robust, and timely data exchange.<sup>9</sup>

**Figure 3. 5G Use Cases**



Sources: ITU, 2018.

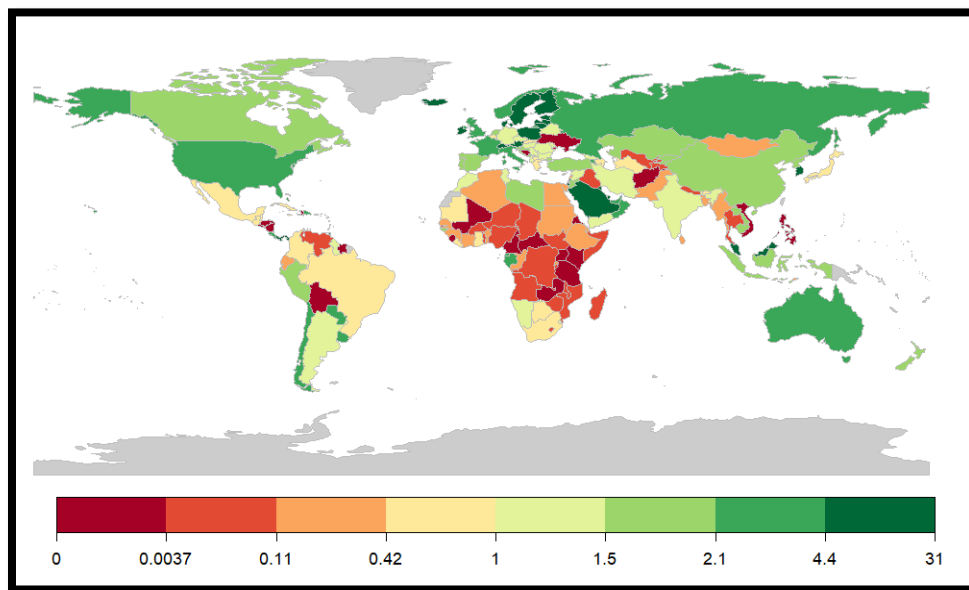
### C. MOBILE DIGITAL DIVIDE

**21. Despite the proliferation of mobile phones, there remains a global mobile Digital Divide.** SSA remains the fastest expanding region in terms of the number of mobile subscribers, with a composite average growth rate of 4.6 percent per year and an additional

<sup>9</sup> A mission critical factor is defined as any factor that is substantial to business operation or to an organization, which failure or disruption may lead to the serious repercussions.

167 million subscribers expected to materialize over the period to 2025 (GSMA, 2019a). In other words, the total subscriber base will increase to slightly over 600 million, representing around half the population.<sup>10</sup> While the increased availability of smartphones has already resulted in increased internet access across the socio-economic spectrum globally, there is still substantial heterogeneity across the world in terms of average monthly mobile data consumption (often referred to as average monthly traffic), measured in gigabytes (GB) per person (Figure 4). For instance, while there are several countries with subscribers' average monthly traffic exceeding 10 GB (Kuwait, 31 GB; Finland, 23 GB; Saudi Arabia 13 GB), there are also economies in which subscribers are consuming on average less than 0.08 GB monthly per capita (Afghanistan, Ukraine, and Bolivia). Moreover, in SSA, subscribers in only three countries consume more than 2.03 GB per month (global average): Seychelles, Equatorial Guinea, and Gabon. Alper and Miktus (2019) note the narrowing of the global Digital Divide from 2005 to 2017. Nevertheless, in the absence of active policies to address issues that hinders progress in infrastructure, affordability, knowledge, quality, and internet access, the global Digital Divide may persist—or even widen—in an environment characterized by far-reaching changes in technology, climate, and global economic integration.<sup>11</sup>

**Figure 4. Average Monthly Mobile Traffic (GB per capita)**



Sources: ITU's ICT Indicators database and authors' calculations.<sup>12</sup>

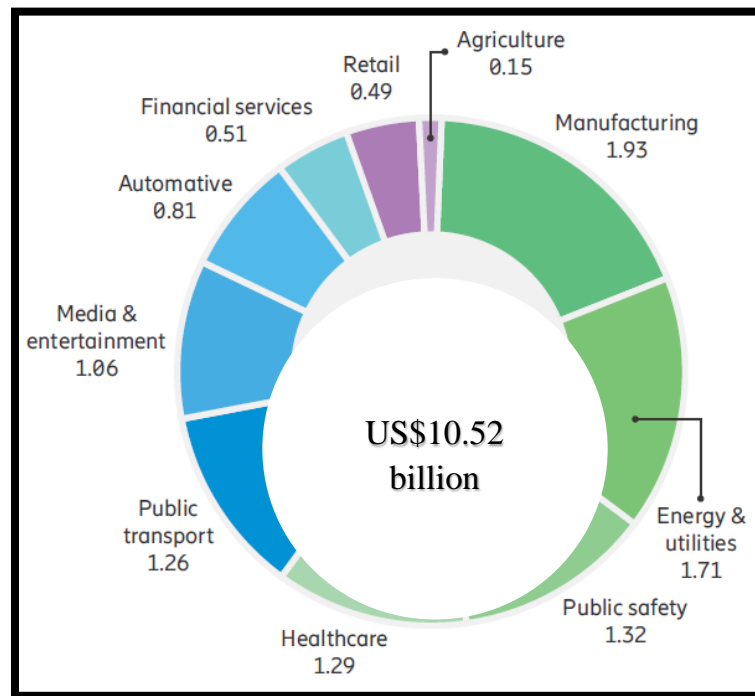
<sup>10</sup> Coetzee and others (2018) foresee mobile subscriptions in SSA to exceed 900 million by 2023.

<sup>11</sup> See Abdychev and others (2018) on factors affecting the future of work in SSA and Alper and Miktus (2019) on the construction of digital connectivity sub-indices of infrastructure, affordability, knowledge, quality, and internet access.

<sup>12</sup> For countries missing average monthly mobile consumption per capita data, we use predicted values based on a linear regression of monthly average traffic per capita as the dependent variable on GDP per capita in PPP terms, its square, ratio of population in the largest city (as percent of the urban population), the rural population (as the percent of total population) and geographic regional dummies. Regression results are available from the authors upon request.

**22. The advanced mobile ecosystem is expected to contribute significantly to economic growth and bridging the mobile Digital Divide emerges as a key policy priority.** Digitalization is estimated to contribute US\$12.3 trillion of global economic output by 2035, with the highest progress in sales activity (HIS, 2017). In SSA, mobile technologies and services already generate US\$144.1 billion, about 8.6 percent of SSA GDP in 2018 (GSMA, 2019a). Moreover, the contribution of 5G in Africa is projected to reach USD 10.5 billion by 2026 from virtually zero currently, with the highest shares expected to materialize in the manufacturing and energy sectors (Figure 5).

**Figure 5. Projected Contribution of 5G by Sector in Africa by 2026**



Sources: Ericsson, 2017.

**23. In addition to contributing to new high-tech employment opportunities, 5G has the potential to revolutionize existing rural jobs, particularly in agriculture.** Recent evidence suggests that the arrival of fast Internet in Africa led to increased employment in both high and low skilled occupations (Hjort and Poulsen, 2019). 5G technology can increase agricultural productivity, for instance by allowing a quicker transfer of data related to weather. Apart from promoting jobs, 5G can improve network connectivity in rural schools, enabling students to achieve more efficient learning (Ovum, 2018), for instance through the wider access to information and knowledge. Local government services are also expected to be positively affected by better mobile connectivity, akin to positive impact of connectivity on the provision of health care services to rural populations.

**24. Active policy intervention would be needed to implement 5G technology to bridge the mobile Digital Divide.** In the early stage of deployment, the investment in 5G will be

commercially viable solely for densely populated urban areas. Consequently, rural and suburban areas would risk falling behind in 5G coverage, further widening the Digital Divide, at least initially. As mentioned earlier, apart from closing the infrastructure gaps, affordability and knowledge issues already contribute to current mobile Digital Divide and these effects could persist, given that poorer and rural households may not be able to afford *smart* devices or if they lack the knowledge to use them. The gender dimension of digital divide is also another area where policy intervention is required consistent with finding that leveling the playing field for female entrepreneurs is to be positively related to higher digital connectivity (Alper and Miktus, 2019).<sup>13</sup> Taking all the above-mentioned points into consideration, choosing the right set of policies for 5G network implementation is crucial to pursue in the SSA region.<sup>14</sup>

### III. COSTING METHODOLOGY

**25. In this section, we illustrate the modern cellular network costing quantitative framework developed by Lombardo (2019).** We start by evaluating the costs related to the full introduction of 4G networks in SSA by 2025. The estimates take account of population density projections and current 4G coverage. Next, we assess implementation of 5G by 2040, assuming the full implementation of 4G by 2025. We estimate the costs involved in providing universal coverage of the population.<sup>15</sup>

**26. The costing methodology accounts for significant heterogeneity across SSA.** First, the SSA economies differ in terms of current 4G technology adoption (Appendix I), hence those lagging in mobile digital connectivity need to bear a higher cost to achieve full 4G coverage by 2025 and satisfactory level of 5G ratification by 2040, conditional on the full implementation of 4G by 2025. Second, there are significant differences in population growth rates as well as the pace of urbanization not only across SSA region, but within different regions in a specific country as well, implying heterogeneity of costs and pointing out the importance of relevant policies in order to provide the equal modern cellular technologies availability across whole country. Finally, we also account for heterogeneity in electricity prices.

**27. We use GADM and WorldPop databases to assess population densities by administrative area.** For every country in SSA, we start by obtaining the spatial data from

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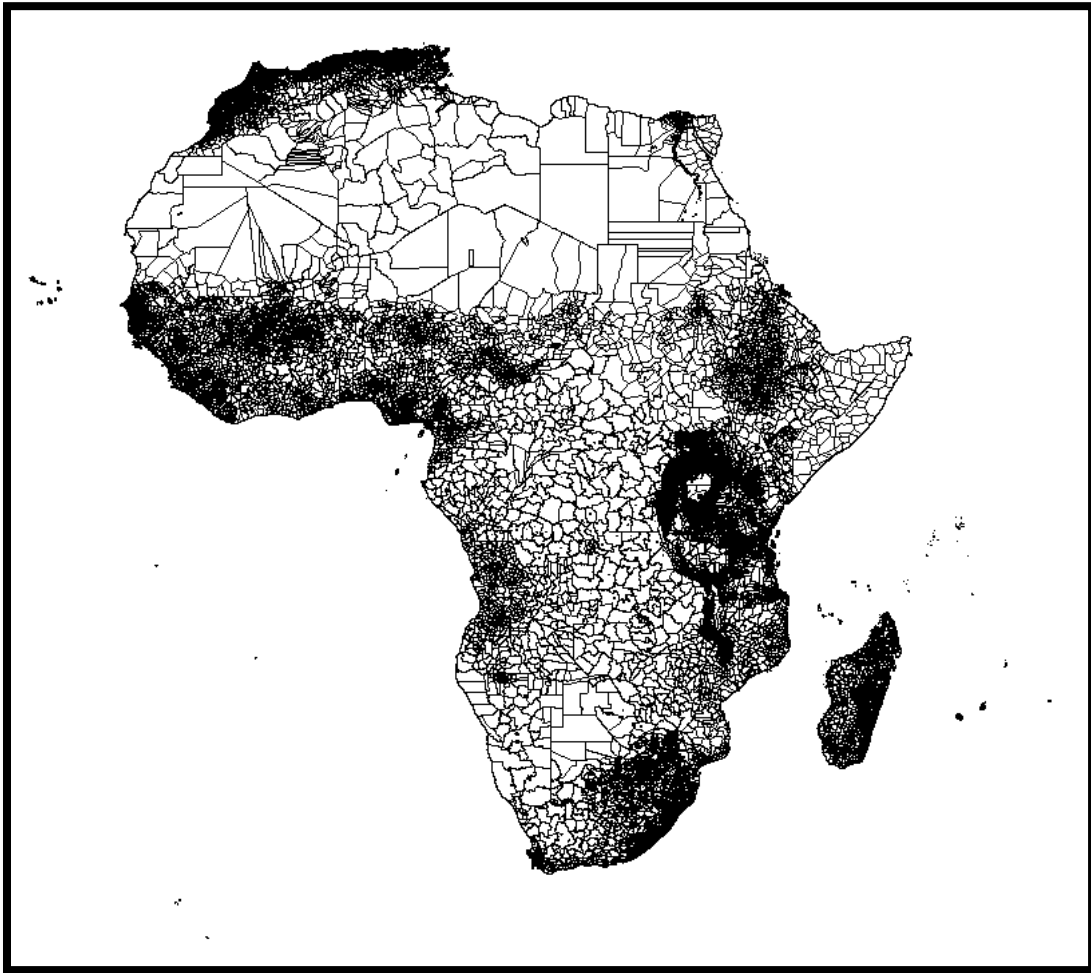
<sup>13</sup> Among others, see Silver and Johnson (2018), Mutsvairo and Ragnedda (2019) on gender aspects of digital divide in Africa.

<sup>14</sup> We do not preclude other potential connectivity schemes that could reduce Digital Divide in SSA (satellite wifi hotspot project of Facebook or TV white space project of Microsoft). There is a possibility that the 5G technology may evolve before 2040 (coming online of post-5G technologies). In other words, countries should consider all available digital connectivity options based on changes in technology.

<sup>15</sup> Throughout the paper all calculations are done using R and Python software.

GADM at the finest level of granularity (Figure 6).<sup>16</sup> Next, we download from the WorldPop database information on population and area for each SSA country as pictures, with pixel intensities quantifying the number of inhabitants for 2000, 2010, and 2020.<sup>17</sup> The predicted number of people per ~100 m pixel is estimated using the random forest model, as described in Stevens and others (2015).

**Figure 6. Administrative Areas for Africa**



Sources: GADM database and authors' calculations.

**28. Population densities for 2025 and 2040 are projected through Lagrange polynomials.** Having three distinct nodes (2000, 2010, and 2020) for each administrative area, in each SSA country, defined as the percentage of population living in a given area to the overall population, quadratic Lagrange polynomials are calculated. The projected population

<sup>16</sup> The coordinate reference system is longitude/latitude and the World Geodetic System 84 datum.

<sup>17</sup> An overview of the data can be found in Tatem and others (2017), while a description of modeling methods is included in Stevens and others (2015).

densities in 2025 and 2040 are then obtained as the values of such polynomials<sup>18</sup> in 2025 and 2040, respectively, multiplied by the ratio of projected population size (from medium-variant projections of the UN for each country) to the current region's area.<sup>19</sup>

**29. We use the costing framework of Lombardo (2019) which draws on data on mobile traffic demand per user, network capacity per user, and the throughput needed in each region.**<sup>20</sup> We obtain the current mobile traffic demand for each SSA country from the ITU ICT Indicators database as the average monthly mobile data consumed per month per capita in GB.<sup>21</sup> We then calculate the busy hours traffic in megabytes per hour per capita by first converting GB to megabytes through multiplying by 1000, converting months to days by dividing by 30 and finally assuming that the hourly busy data consumption accounts for 20 percent of the total daily traffic. Next, we calculate the busy hour bitrate which serves as an input to the network capacity computation. We convert megabytes per hour to megabits per second by multiplying by 8 and then dividing by 3600 (60 x 60). Then we compute the network capacity by assuming that the network should be able to provide at least 80 percent of busy hour bitrate all the time. Finally, the projected population densities are multiplied by network capacities to derive the area throughput (Box 1).

**Box 1: Calculating Area Throughput**

$$\text{Busy hour traffic} = 0.2 \cdot 1000 \cdot \frac{\text{Monthly traffic}}{30}$$

$$\text{Busy hour bitrate} = 8 \cdot \frac{\text{Busy hour traffic}}{60 \cdot 60}$$

$$\text{Network capacity} = \frac{\text{Busy hour bitrate}}{0.8}$$

$$\text{Area throughput} = \text{Network capacity} \cdot \text{Population density}$$

**30. Our network costing methodology incorporates population growth and rapid urbanization within each administrative area in every SSA country.** Population densities in highly disaggregated administrative areas enter as inputs to the required area throughput

<sup>18</sup> Due to the unboundedness of the projected weights, we truncated the distribution by assigning values greater than 1 to 1 and smaller than 0 to 0. To ensure all weights sum to 1, we divide each weight by their sum. We also considered an alternative approach by applying soft-max transformation to the projected weights. However, this led to marginal variability of population densities across regions and thus we dropped it.

<sup>19</sup> We assume unchanged administrative areas in the next two decades. We initially considered applying the weights of administrative areas in 2020 to 2025 and 2040 to project population densities in each administrative area but decided not to proceed as it would ignore rapid urbanization in SSA.

<sup>20</sup> Area throughput is a technical term that defines data transfer speed per area for a given amount of energy.

<sup>21</sup> For countries with missing average monthly mobile consumption per capita data, we use predicted values based on a linear regression of monthly average traffic per capita as the dependent variable on GDP per capita in PPP terms, its square, ratio of population in the largest city (as percent of the urban population), the rural population (as the percent of total population) and geographic regional dummies. Regression results are available from authors upon request.

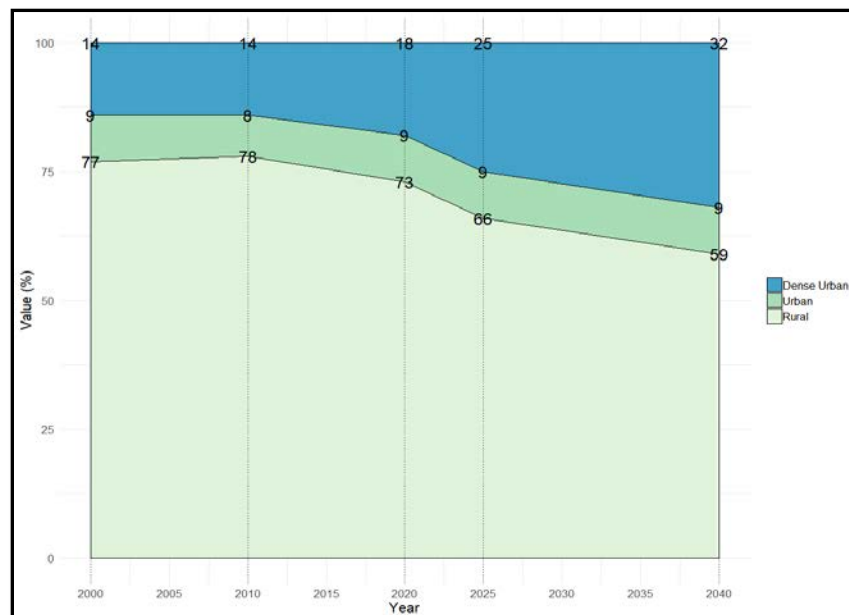
calculation. We also use population densities to classify each area into three broad urbanization categories to account for specific cell characteristics in the costing framework (Table 1).

**31. We next include population information to obtain population density in each administrative region.** Specifically, we download information about population for each country from the WorldPop database. Pixel intensities within each country provides information about the number of inhabitants. We then juxtapose the population intensity map with boundaries of administrative areas obtained from GADM database. An illustrative example for Rwanda in Appendix III.

**32. We next categorize the regions into three groups: *Rural*, *Urban*, or *Dense Urban*.** An administrative area is designated as *Rural* when its population density is less than 500 people per square kilometer; *Urban* when the population density is greater than 500, but less than 1,500 people per square kilometers; and finally, an administrative area is designated as *Dense Urban* when the population density exceeds 1,500 people per square kilometer.<sup>22</sup>

**33. Our projections show a significant increase in share of densely urban population** (Figure 7). Based on our projections from the fitted Lagrange polynomials, share of population in rural areas in SSA would fall to less 60 percent by 2040 from 78 percent in 2010. At the same time share of population in densely urban areas is projected to increase to roughly a third of the total population in SSA from below 15 percent in 2010.

**Figure 7. Share of Population in Rural, Urban and Dense Urban Areas in SSA**



Sources: GADM and WorldPop database and authors' calculations.

<sup>22</sup> Jedwab and others (2019) argue that population density is not necessarily a satisfactory measure of urbanization and city size. Replication of this exercise, by including regional income or the level of urban technology when such data is available could be a valuable extension of this paper.

**34. Rapid urbanization poses a challenge for determining the necessary infrastructure to implement the 5G cellular network.** Based on the population density projections for each administrative area and the UN’s medium variant population projections for each country in 2025 and 2040, we plot the share of population living in the three urbanization groups in SSA and observe the migration away from rural areas towards densely urban areas and specifically the emergence of mega-cities in SSA by 2040. Urbanization and overall rising population need to be accompanied by an increase in infrastructure, including the proper investments in both 4G and 5G cellular network technologies. Higher population density will likely lead to higher costs, reflecting higher reliance on more expensive micro- and pico-cells in the presence of increasing structures in such city centers.

**35. We then provide key parameter values of the mobile network infrastructure.** Based on the actual list of spectrum allocations per country in SSA,<sup>23</sup> we assume that the macro-cells will operate on 700 MHz,<sup>24</sup> the micro-cells on 1800 MHz, and the Pico-cells on 2600 MHz.<sup>25</sup> Furthermore, all cell types are assumed to possess 15 bit/s/Hz efficiency for the 4G, while 23 bit/s/Hz for the Fifth-Generation network. Finally, cell radiuses depend on population densities, and for the sake of simplification are clustered into three broad groups, in the manner outlined in Table 1.

**Table 1. Cell Radius and Population Density**

<b>Geotype</b>	<b>Macro cell</b>	<b>Micro cell</b>	<b>Pico cell</b>
<b>Rural</b> (0 – 500 pop/km <sup>2</sup> )	10 km	2 km <sup>26</sup>	Not applicable
<b>Urban</b> (500 – 1500 pop/km <sup>2</sup> )	2.5 km	1.25 km	0.2 km
<b>Dense Urban</b> (>1500 pop/km <sup>2</sup> )	1 km	0.5 km	0.1 km

Source: Lombardo (2019).

**36. We assume hexagons to represent the cell coverage in the network, as commonly done in the literature.** Johansson (2007) shows that the number of base stations for heterogenous networks with a uniform traffic distribution can be approximated either by the maximum average aggregate throughput or the cell range (the coverage). Given that the

<sup>23</sup> See <http://www.spectrummonitoring.com/frequencies/>.

<sup>24</sup> Another possibility is to operate at 800 MHz (CSIR, 2018). It is important to underscore that each spectrum has different physical characteristics, leading to trade-offs between capacity, coverage, latency, reliability, and spectral efficiency.

<sup>25</sup> Much higher frequencies and greater bandwidth for higher data rates are currently being commercially tested, for instance AT&T in the USA at 28 GHz (EC, 2016).

<sup>26</sup> Lombardo (2019) considers 5 km radius for micro cells in rural areas. We take a more conservative approach and in spirit of BU-LRIC model (Analysys Mason, 2017) assume 2 km radius for micro cells in SSA.



primary concern of the paper is to find the cost of bridging the mobile Digital Divide and thus delivering the improved connectivity for everyone and everywhere, we assume that implementation of a network that prioritizes coverage is the highest priority. Consequently, for a hexagonally shaped cell of class  $i$ , where  $i \in \{\text{Macro, Micro, Pico}\}$ , identified by the maximum radius  $r_i$ , we calculate the required number of base stations to serve the area of size  $A$  by:

$$n_i = \frac{2A}{3\sqrt{3}r_i^2}$$

Furthermore, assuming a maximum capacity  $\tau_i$ , we calculate the throughput provided by  $n_i$  base stations of class  $i$  in an area of size  $A$ :

$$T_i = \frac{\tau_i \cdot n_i}{A}$$

If the estimated throughput is unable to satisfy demand, it is possible to either strengthen the network by supplying additional stations of class  $i$  (if there are supplementary providers in the region) or to provide an extra layer of stations of a different class.<sup>27</sup>

**37. The projected costs are subject to upside risks.** The estimates do not include costs associated to possible signal loss generated by topology (for instance, vast mountain areas or deserts) or interference (a significant number of microwaves or unexpected lighting and other violent electrostatic discharges). Instead, we assume constant throughput in the entire service area. The calculated costs should thus be seen as a lower bound. A more sophisticated cost analysis, such as the SEAMCAT model (Oughton and others, 2019), or the nonlinear constrained discrete demand/coverage/capacity optimization approach (Schneir and others, 2017) could be therefore viewed as a valuable extension, but data requirements do not allow us to undertake these for all SSA countries.

**38. We next calculate the number of required cells for each administrative area in each SSA country.** Starting with the macro-cells, we compute the maximum number of cells to be installed in each administrative area to guarantee full coverage, simultaneously calculating their delivered throughput. When 4G/5G mobile demand is fully satisfied, we move to the next region, otherwise we tend to the densification need. We assume *multiple input, multiple output technology*, which combines up to three antennas for a single cell, minimizing transmission error and optimizing data speed. In other words, we start with a single cell with a single transmitter and consecutively we supplement additional antennas (up to three) to increase the capacity. If demand is still not satisfied, we consider two scenarios: if other carriers are present in a given area (see Appendix II), we add other macro-cell layers (with up to three

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<sup>27</sup> An alternative approach would be to estimate the demand and the predicted number of users through the Bass model (Smail and Weijia, 2017).

transmitters)<sup>28</sup> If the demand is not yet fulfilled, we add other micro-cell layers (if there are other telecoms operating in the region) or pico-cells until the area throughput satisfies the demand. Finally, since the results obtained consider the situation where the technology used is the highest performing for every single cell, we follow Lombardo (2019) and augment the number of cells by 30 percent (Lombardo, 2019). We repeat this procedure and calculate the number of cells for years for 2020, 2025, and 2040 as below.

- **Calculating number of cells in 2020.** We initially assume that the current mobile consumption traffic is uniformly distributed across every administrative area of a country. For 2020 only, we consider an additional step: the final number of cells in a given region is set equal to the product of the percentage of population covered by the 4G network and the number of cells given by  $n_i$ .
- **Calculating number of cells under two scenarios for 4G network in 2025.** Under the first scenario, we assume that 23 percent of connections in 2025 are made available through the 4G network, compared to seven percent in 2018 (GSMA, 2019a). We also impose an additional constraint guaranteeing a minimum of 0.5 GB monthly mobile traffic by 2025. Under the second scenario, we use the world mean monthly consumption 5.6 GB and its projected value of 20.1 GB by 2024 (Ericsson, 2019). Using the values that underlie Figure 5, we estimate current global average monthly traffic to equal 2.03 GB. Hence, based on the initial condition differences, we adjust the 2025 Ericsson (2019) goal to equal  $\frac{2.03}{5.6} \cdot 20.1 = 7.3$  GB monthly traffic in the second scenario.<sup>29</sup>
- **Calculating number of cells for 5G network in 2040.** We follow the European Broadcasting Union objective of guaranteeing a minimum of 44 GB of monthly mobile traffic by 2040. This goal *does not* imply that the entire SSA will be using 44GB of mobile data, particularly considering the relatively low smartphone adoption rate at 39 percent currently, predicted to rise to 66 percent by 2025 (GSMA, 2019). Nevertheless, our estimates provide the cost of the infrastructure that would be needed. To allow this use of 44GB of data.

**39. Finally, we calculate network costs.** We distinguish between two main cost components: capital and the operating expenditures (Pereira, 2007). The capital expenditures component (Capex) includes equipment costs, tower costs, and installation costs, paid at the beginning of each year for simplicity. The operating expenditures component (Opex) incorporates energy consumption, heat dissipation, the site rental, and site operation and maintenance expenses (O&M), paid at the end of the year. The input numbers are given in Table 2. The electricity costs per kW/h are from the World Bank database, following the DB16-

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<sup>28</sup> We do not assume that the same carriers will operate in a given country in the next decade, nevertheless we impose a constant number of carriers.

<sup>29</sup> Throughout the text, the first scenario will be referred to as the GSMA objective, while the second one as the Ericsson goal.

19 methodology and are assumed to remain constant in the next two decades. The heat dissipation component is assumed to double electricity costs. Moreover, the operational expenses include the labor costs which reflect the 6–7 days of work of an expert annually for the macro cells and 2-4 days of work for the micro- and pico-cells. In addition, we assume the operators share parts of Capex and Opex costs (see Box 2). We assume expert availability in every region, which may underestimate the actual costs especially in low-income areas with scarcity of skilled labor. To account for such costs and in general large uncertainty characterizing the 4G/5G costs in SSA, the final costs are augmented by 30–50 percent.<sup>30</sup>

**Table 2. Mobile Network Costs<sup>31</sup>**

**Capital Expenditures<sup>32</sup>**

Site categorization	Equipment	Tower	Installation
Macro	€2k	€123k	€30k
Micro	€k	€20k	€10k
Pico	€k	€3k	€k

**Operational Expenditures**

Site categorization	Power	Efficiency <sup>33</sup>	O&M	Rental
Macro	100 W	50%	€3.3k	€5k
Micro	50 W	50%	€1k	€2.5k
Pico	10 W	50%	€0.9k	€0.01k

Source: Lombardo (2019).

<sup>30</sup> Oughton and Frias (2018) augment total cost by 10 percent for the United Kingdom. We choose 30-50 percent to reflect the sparse availability of fiber backhaul in SSA and to account for secondary costs such as air conditioning equipment. We use a 50 percent mark-up for Capex in light of the inefficiency of investment in SSA and 30 percent for Opex in SSA. We also do not discount costs for potential competitive bidding dynamics outlined in Federal Communications Commission (2010).

<sup>31</sup> The exchange rate is assumed to remain constant at 1.1 US\$/EUR.

<sup>32</sup> Lombardo (2019) considers macro-cell equipment Capex cost of €5k, and macro-cell tower Capex of €20k. Numerous studies for Africa project the overall macro-site Capex to the order of magnitude around €100k-€300k, including Facebook (2015), World Bank Group (2015), and World Economic Forum (2017). We follow Facebook (2015), augmenting the aforementioned costs to €32k (\$35k, assuming the constant exchange rate 1.1 US\$/EUR) and €123k (\$135k) respectively, which translates to the overall macro-site Capex of €185k.

<sup>33</sup> This implies a doubling of energy consumption costs. Implementation of modern energy savings schemes can lead to up to 17% energy savings in macro-cells and up to 33% in micro-cells (Sharma, 2017), similar to the gains from proper air conditioning (Deruyck and others, 2014).

**Box 2: Calculating Network Costs**

$$\text{Capex} = \sum_{i=1}^{\text{Class}} \sum_{j=1}^{\text{Cells}} \text{Equipment}_{i,j} + \sum_{k=1}^{\text{Sites}} (\text{Tower}_k + \text{Installation}_k)$$

$$\text{Opex} = \sum_{i=1}^{\text{Class}} \sum_{j=1}^{\text{Cells}} (\text{Energy\_consumption}_{i,j} + \text{Heat\_dissipation}_{i,j}) + \sum_{k=1}^{\text{Sites}} (\text{Rental}_k + \text{O\&M}_k)$$

**40. Projected investment costs account for the lifetime of the equipment.** The passive part, “Tower” component of Capex has an estimated lifetime of around 20-30 years, thus it does not need to be renewed until 2040. On the other hand, the active part, “Equipment” component, has a lifetime range of around 5-10 years which necessitates renewal of active equipment investment in 2020 to be renewed twice, in both 2032 and 2040 and the renewal of 5G additional cells at least once. We do not have dedicated “Installation” costs for “Tower” and “Equipment” components, and we assume that installation costs are incurred for each equipment renewal cycle.<sup>34</sup>

**41. The current mobile Digital Divide and differences in population growth rates and urbanization are significant inputs in the costing framework.** There is considerable heterogeneity among SSA countries in terms of mobile technology availability and hence those lagging in mobile digital connectivity need to bear a higher cost to achieve full 4G connectivity by 2025. In addition, 5G costing is conditional on the full implementation of 4G by 2025 and differences in population growth rates as well as the pace of urbanization would imply heterogeneity of costs across SSA countries in 2040.

#### IV. TOTAL COST OF 4G AND 5G CONNECTIVITY IN SSA

**42. We next present the estimated annual costs of introducing a full-scaled 4G network by 2025 and operable 5G network by 2040 in SSA.** We calculate total costs for SSA, assuming Ericsson (2019) goals for 4G in 2025 and the decreased radius of macro-cells in rural areas scenario in 2040<sup>35</sup>. We also provide cost estimates for Capex and Opex compo-

<sup>34</sup> We assume fixed equipment price from 2020–40. A potential refinement in the costing framework could include 5 to 10 percent annual reduction in unit cost of an active equipment to reflect technological progress or investment increase in all the technical network value chain, for example reflecting switching from microwave backbones to fiber backbones to sustain the traffic demand.

<sup>35</sup> We present the results for the Ericsson goal due to their similarity to the outcomes obtained through the second scenario, while providing significantly higher data traffic. Moreover, we choose to consider the decreased radius of macro-cells, because of the uncertainty that the higher radius cells could in fact deliver the desired throughput. The results of alternative scenarios are available from the authors upon request.

nents for SSA; and annual costs for SSA as well as at the country level. Our results indicate significant heterogeneity in terms of required infrastructure and servicing needs. All costs, included in Appendix V, are expressed both in the absolute terms (in USD) and relative to the projected Gross Domestic Product in Purchasing Power Parity terms.<sup>36</sup>

**Figure 8. SSA: Capex and Opex Costs for 4G and 5G**



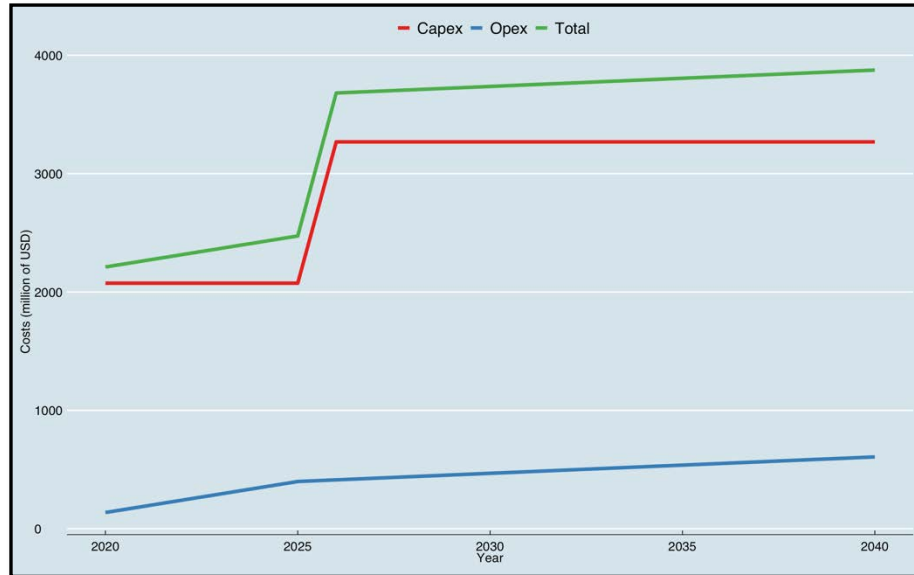
Sources: GADM and WorldPop database and authors' calculations.

**43. Our estimates suggest that the required capital and operational expenditures rise to about US\$14 billion for 4G by 2025 and to US\$57 billion for 5G by 2040.** Specifically, the Capex cost component for 4G amounts to US\$12.5 billion by 2025 for SSA, while its Opex cost corresponds to US\$1.5 billion. Moreover, the 5G Capex cost component is higher in magnitude than in 4G case, reaching US\$49 billion. Similarly, the 5G Opex cost component is significantly higher, at US\$8 billion by 2040 (Figure 8). As discussed earlier, 5G costs are calculated under the assumption that full 4G connectivity is achieved by 2025. We assume that the required Capex spending cost is financed uniformly across years (Figure 9). This assumption implies higher annual Capex cost for 4G implementation by 2025, given that there are only 5 years to finance the required investment. Consequently, annual Capex spending for 5G implementation by 2040 is lower, as the required annual investment is divided uniformly to 15 years (2026-2040). This suggests that countries with insufficient initial 4G infrastructure

<sup>36</sup> The required costs related to Capex and Opex for full 4G connectivity by 2025 are expressed as a ratio of 2025 GDP and for 5G connectivity by 2040 as a ratio of 2040 GDP. The GDP projections through 2024 are from IMF WEO database for August 2019 vintage. Real GDP growth rates for 2025-40 are obtained, where available, from the IMF LIC DSF database, July 2019 vintage, otherwise assumed to remain constant from 2024.

and financing constraints in 2018 might choose to delay the full-scale 4G network implementation to 2030, lowering the significant annual Capex financing needs.

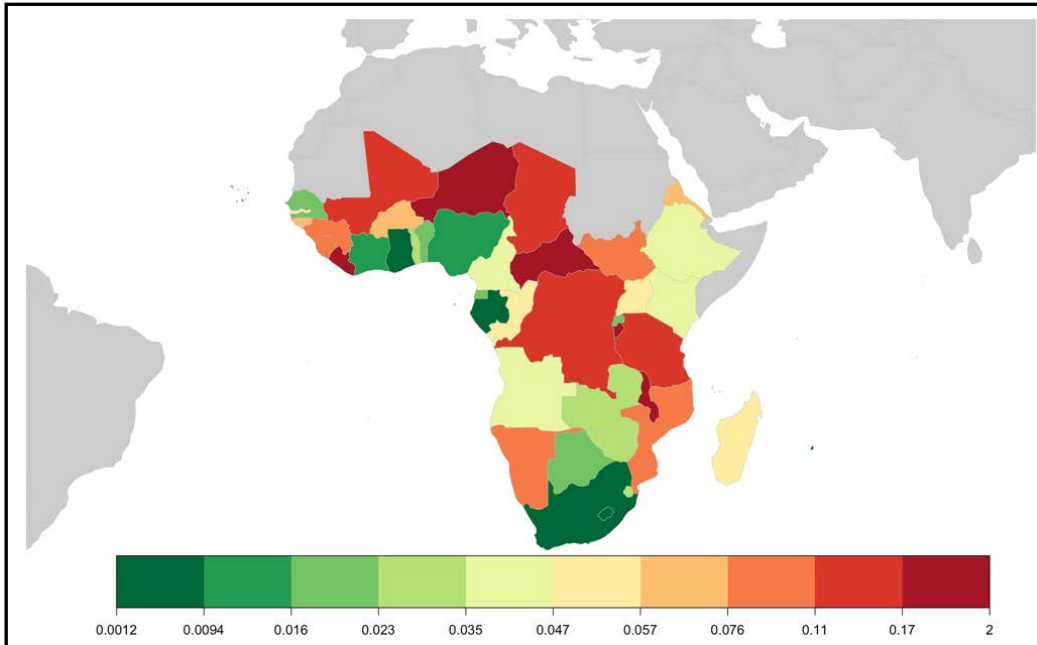
**Figure 9. Evolution of Annual Cost Components for 4G/5G Implementation**



Sources: GADM and WorldPop database and authors' calculations.

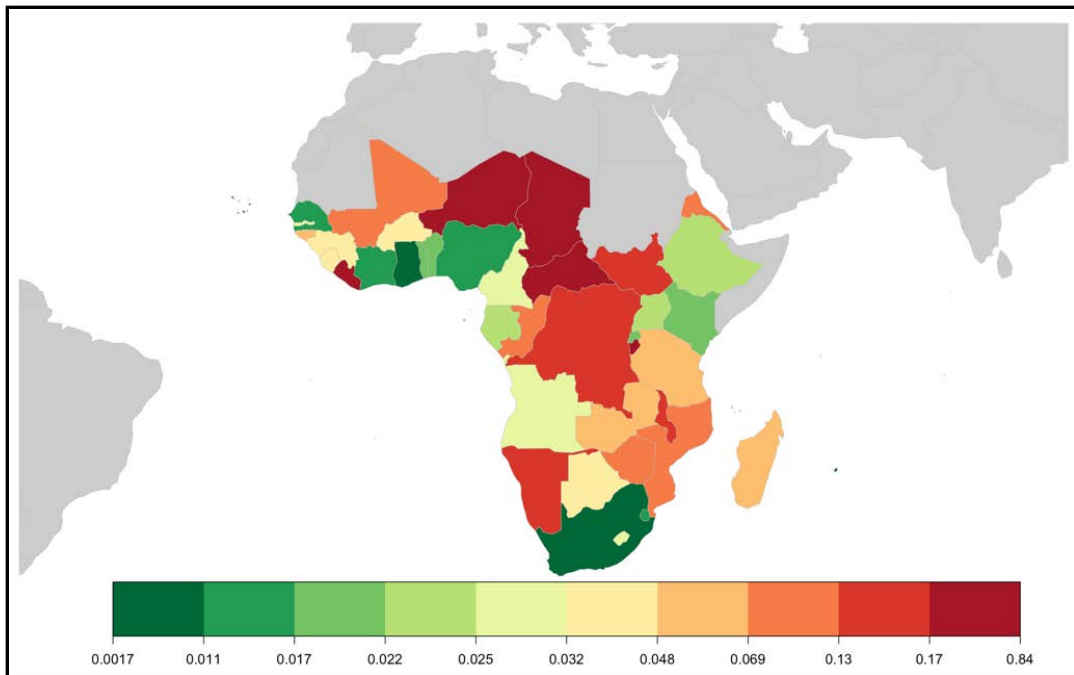
**44. We observe significant heterogeneity in required annual Capex spending needs for 4G/5G implementation across SSA.** Aggregate cost estimates for 4G implementation suggest that the required Capex- and Opex-related costs climb annually to approximately US\$2.5 billion (0.04 percent of SSA GDP) by 2025. While total spending needs for Mauritius and South Africa are less than 0.004 percent of GDP annually, for Burundi the total annual cost reaches 2 percent of GDP (Figure 10), reflecting chiefly the current low level of its infrastructure. Similarly, overall costs of implementing 5G amount to US\$3.9 billion (0.03 percent of SSA GDP) annually in 2040 with significant heterogeneity across the region. While required 5G annual costs for Mauritius, Seychelles and Ghana are less than 0.01 percent of their projected GDP, annual costs for Burundi stands at 0.36 percent GDP and for Central African Republic at 0.85 percent of GDP (Figure 11), reflecting differences in growth rates of population and real GDP as well as the projected pace of urbanization. We also note that a significant part of the total costs owes to the extent of the rural areas (Figure 12).

**Figure 10. Annual Cost of Full-Scaled 4G Network in 2025**  
(as percentage of GDP)

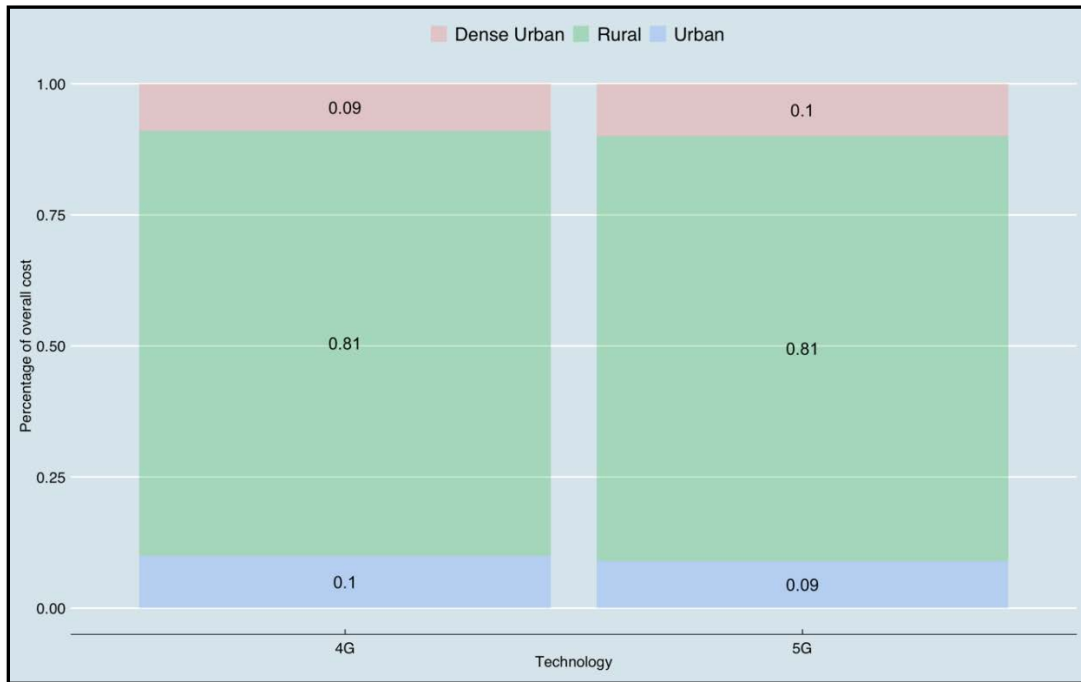


Sources: GADM and WorldPop database and authors' calculations.

**Figure 11. Annual Cost of Operable 5G Network in 2040**  
(as percentage of GDP)



Sources: GADM and WorldPop database and authors' calculations.

**Figure 12. Cost Evolution and Population Density**

Sources: GADM and WorldPop database and authors' calculations.

**45. Finally, we consider total costs per subscriber using projected penetration rates.** Implementation of full 4G by 2025 costs correspond annually to 8.4 percent of average subscriber income in SSA in 2025, while implementation of 5G by 2040 costs 4.9 percent of subscriber income annually in 2040 on a median basis. We obtain these using the estimated costs, projected GDP and the population size and by linearly extrapolating for 2025 and 2040 the estimates of the penetration rate for SSA in 2017 from GSMA Intelligence. Specifically, we calculate the per subscription income costs using the following formula:

$$\frac{\text{Annual total cost}}{\text{Unique subscribers}} / \frac{\text{GDP}}{\text{Population}} = \frac{\text{Annual total cost}}{\text{Population} \cdot \text{Penetration rate}} / \frac{\text{GDP}}{\text{Population}} =$$

$$= \frac{\text{Annual total cost}}{\text{Penetration rate} \cdot \text{GDP}}$$

The values for 4G in 2025 and 5G in 2040 for each SSA country are included in the Appendix V.

## V. CONCLUDING REMARKS

**46. 5G technology could help bridge the mobile Digital Divide in SSA.** The materialization of the benefits from reducing the mobile Digital Divide would depend on successful policy interventions to address issues beyond the provision of the necessary infrastructure. These include affordability and knowledge, as well as additional considerations such as cybersecurity and data privacy, that are beyond the scope of this paper.



**47. The rollout of 5G technology demands a significant investment in infrastructure.**

The Fifth-Generation cellular network requires more cells, capable of providing sufficient capacity. We adopt the costing model of the European Broadcasting Union to SSA by accounting for a host of factors including demographic change, urbanization, heterogeneity in current mobile infrastructure, and electricity costs. Our estimates suggest that the required capital and operational expenditures climb to approximately US\$14 billion for 4G by 2025 and to US\$57 billion for 5G by 2040. In annual terms, we project median annual costs to roughly correspond to 8.4 percent of subscriber income in 2025 and 4.9 percent of annual subscriber income by 2040 with significant heterogeneity across countries. Who should bear this cost? Should it be the public sector or consumers/firms? Should countries with significant mobile connectivity costs consider delaying the 4G connectivity say until 2030 and reduce annual capital spending needs at the cost of delaying the catch up? Given the poverty levels, competing spending needs including on education, health, affordable electricity access, and water and sanitation, these are important policy discussion that needs to be addressed subsequently by the policy makers. It is especially important regarding the sizable additional spending requirement for SSA to meet the Sustainable Development Goals by 2030, estimated at US\$400 billion (0.4 percent of 2030 world GDP), reflecting the region's lag in development.

**48. Policy interventions to facilitate a more enabling environment for mobile operations is needed to complement infrastructure spending.**

Regardless of whether the private or public sector pays for the new infrastructure, policy action to encourage competition, implement appropriate licensing frameworks to achieve inclusive coverage, and address tax issues that hamper the provision of mobile services are needed. Policymakers and telecoms regulators play a crucial role in ensuring affordable connectivity for everyone, including addressing gender divide. There are several creative country examples of how countries can address these issues. Countries could consider, for example, selling the available spectrum to the telecommunication companies under the condition of furnishing full geographical coverage, similar to the approaches followed by Germany or Australia. Supportive legislation should establish a forward-looking national strategy and time-bound targets to expand digital connectivity opportunities beyond mobile. Directed subsidies in the rural areas and by gender, for instance, in the form of free sim cards or costless subscriptions or incentives to increase affordability of smartphones, could also be used to complement infrastructure availability.

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**APPENDIX I. 4G Coverage in SSA**  
(in percentage)

Country	ISO	4G Coverage	Year	Country	ISO	4G Coverage	Year
Angola	AGO	8	2017	Lesotho	LSO	80	2017
Benin	BEN	39.72	2017	Liberia	LBR	4.4	2016
Botswana	BWA	65	2017	Madagascar	MDG	23.08	2017
Burkina Faso	BFA	0	2017	Malawi	MWI	30	2017
Burundi	BDI	11	2017	Mali	MLI	0	2016
Cabo Verde	CPV	76.5	2014	Mauritius	MUS	93	2017
Cameroon	CMR	0.76	2016	Mozambique	MOZ	0	2017
Central African Rep.	CAF	0.14	2016	Namibia	NAM	39	2017
Chad	TCD	22.01	2016	Niger	NER	0	2017
Comoros	COM	73	2017	Nigeria	NGA	50.84	2017
Congo (Rep. of the)	COG	5	2016	Rwanda	RWA	89	2017
Cote d'Ivoire	CIV	47	2017	Sao Tome and Principe	STP	0	2015
Dem. Rep. of the Congo	COD	0	2017	Senegal	SEN	21.6	2016
Equatorial Guinea	GNQ	0	2016	Seychelles	SYC	90	2017
Eritrea	ERI	0	2016	Sierra Leone	SLE	0	2016
Eswatini	SWZ	21	2016	Somalia	SOM	18	2017
Ethiopia	ETH	10	2017	South Africa	ZAF	77.62	2017
Gabon	GAB	94	2017	South Sudan	SSD	10	2016
Gambia	GMB	0	2016	Tanzania	TZA	13	2017
Ghana	GHA	34.86	2017	Togo	TGO	0	2016
Guinea	GIN	10.3	2016	Uganda	UGA	17	2017
Guinea-Bissau	GNB	21.44	2016	Zambia	ZMB	43.41	2017
Kenya	KEN	25	2017	Zimbabwe	ZWE	34.72	2017

Sources: ITU ICT indicators database.

## APPENDIX II. List of 4G Networks in SSA

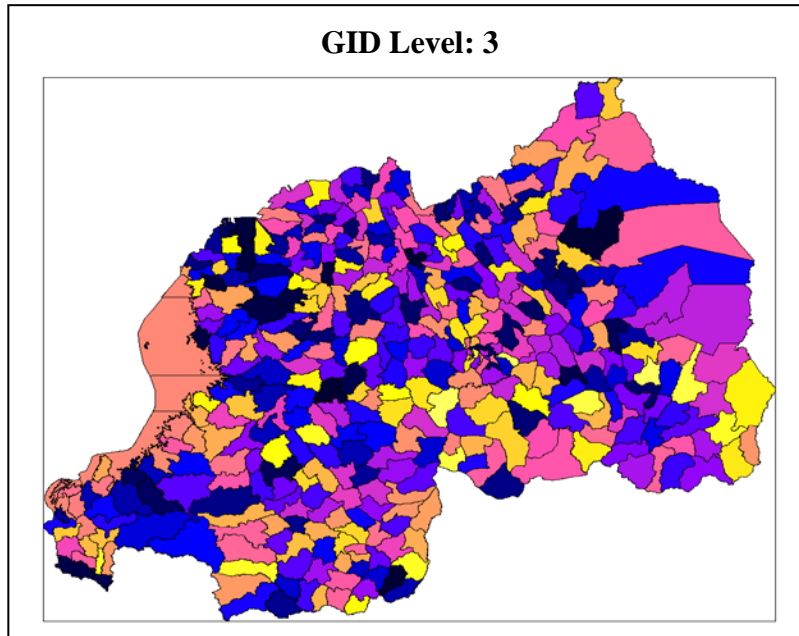
Country	ISO	Operator	Country	ISO	Operator	Country	ISO	Operator
Angola	AGO	Movicel	Ghana	GHA	Blu Telecom	Nigeria	NGA	Spectranet
Angola	AGO	Net One	Ghana	GHA	BusyInternet	Nigeria	NGA	SWIFT
Angola	AGO	Unitel	Ghana	GHA	MTN	Rwanda	RWA	KT Rwanda
Benin	BEN	be.Telecoms	Ghana	GHA	Surflin	Sao Tome and Principe	STP	Cstome
Benin	BEN	MTN	Ghana	GHA	Telesol	Senegal	SEN	Orange
Botswana	BWA	BTC	Ghana	GHA	Vodafone	Seychelles	SYC	Airtel
Botswana	BWA	Mascom	Guinea	GIN	Orange	Sierra Leone	SLE	Orange
Botswana	BWA	Orange	Guinea-Bissau	GNB	Orange	Sierra Leone	SLE	Sierratel
Burkina Faso	BFA	Onatel	Kenya	KEN	Airtel	Somalia	SOM	Globalsom
Burkina Faso	BFA	Orange	Kenya	KEN	Faiba 4G	Somalia	SOM	Sahal Telecom
Burundi	BDI	Econet Leo	Kenya	KEN	Safaricom	Somalia	SOM	Somnet Telecom
Burundi	BDI	Viettel	Kenya	KEN	Telkom Kenya	Somalia	SOM	Somcable
Cabo Verde	CPV	Cabo Verde Telecom	Lesotho	LSO	Vodacom	Somalia	SOM	Somtel
Cabo Verde	CPV	T+ Mobile	Liberia	LBR	Orange	Somalia	SOM	Telesom
Cameroon	CMR	MTN	Madagascar	MDG	Bharti Airtel	South Africa	ZAF	Cell C
Cameroon	CMR	Vodafone	Madagascar	MDG	Blueline	South Africa	ZAF	MTN
Central African Rep.	CAF	Moov	Madagascar	MDG	Orange	South Africa	ZAF	Neotel
Central African Rep.	CAF	NationLink Telecom	Madagascar	MDG	Telma	South Africa	ZAF	Rain Mobile
Central African Rep.	CAF	Orange	Malawi	MWI	Access Comm	South Africa	ZAF	Telkom
Central African Rep.	CAF	Telecel Centrafrique	Malawi	MWI	Airtel	South Africa	ZAF	Vodacom
Chad	TCD	Airtel	Malawi	MWI	TNM	South Sudan	SSD	4GTelecom
Chad	TCD	Tigo	Mali	MLI	Orange	South Sudan	SSD	Niletel
Comoros	COM	Telma	Mali	MLI	Malitel	Tanzania	TZA	Smile
Congo (Rep. of the)	COG	MTN	Mauritius	MUS	Emtel	Tanzania	TZA	Smart
Cote d'Ivoire	CIV	Moov	Mauritius	MUS	MTML	Tanzania	TZA	Tigo
Cote d'Ivoire	CIV	MTN	Mauritius	MUS	my.t	Tanzania	TZA	TTCL
Cote d'Ivoire	CIV	Orange	Mozambique	MOZ	Movitel	Tanzania	TZA	Vodacom
Cote d'Ivoire	CIV	YooMee	Mozambique	MOZ	Vodacom	Tanzania	TZA	Zantel
Dem. Rep. of Congo	COD	Vodacom	Namibia	NAM	MTC	Togo	TGO	Teolis
Equatorial Guinea	GNQ	Orange	Namibia	NAM	Paratus	Togo	TGO	Togocel
Equatorial Guinea	GNQ	HiTs	Namibia	NAM	TN Mobile	Togo	TGO	Moov
Eritrea	ERI	Eritel	Niger	NER	Airtel	Uganda	UGA	Airtel
Eswatini	SWZ	MTN	Nigeria	NGA	Airtel	Uganda	UGA	MTN
Eswatini	SWZ	Swazi Mobile	Nigeria	NGA	Bitflux	Uganda	UGA	Orange
Ethiopia	ETH	Ethiotelecom	Nigeria	NGA	Cyberspace	Uganda	UGA	Smile
Gabon	GAB	Airtel	Nigeria	NGA	Etisalat	Zambia	ZMB	Airtel
Gabon	GAB	Gabon Telecom	Nigeria	NGA	Glo Mobile	Zambia	ZMB	MTN
Gabon	GAB	Moov	Nigeria	NGA	InterC Network	Zambia	ZMB	Vodafone
Gambia	GMB	Africell	Nigeria	NGA	MTN	Zambia	ZMB	Zamtel
Gambia	GMB	Netpage	Nigeria	NGA	ntel	Zimbabwe	ZWE	Econet
Gambia	GMB	QCell	Nigeria	NGA	Smile	Zimbabwe	ZWE	Net*One

Sources: Wikipedia, October 8, 2019.

### APPENDIX III. Country Case Study: Rwanda

1. **Our network costing methodology incorporates population growth and rapid urbanization within each administrative area in every SSA country.** We illustrate the methodology using Rwanda as an example. Figure 8 plots administrative division at the finest possible level of granularity.<sup>1</sup>

**Figure A.III.1. Administrative Areas of Rwanda<sup>2</sup>**

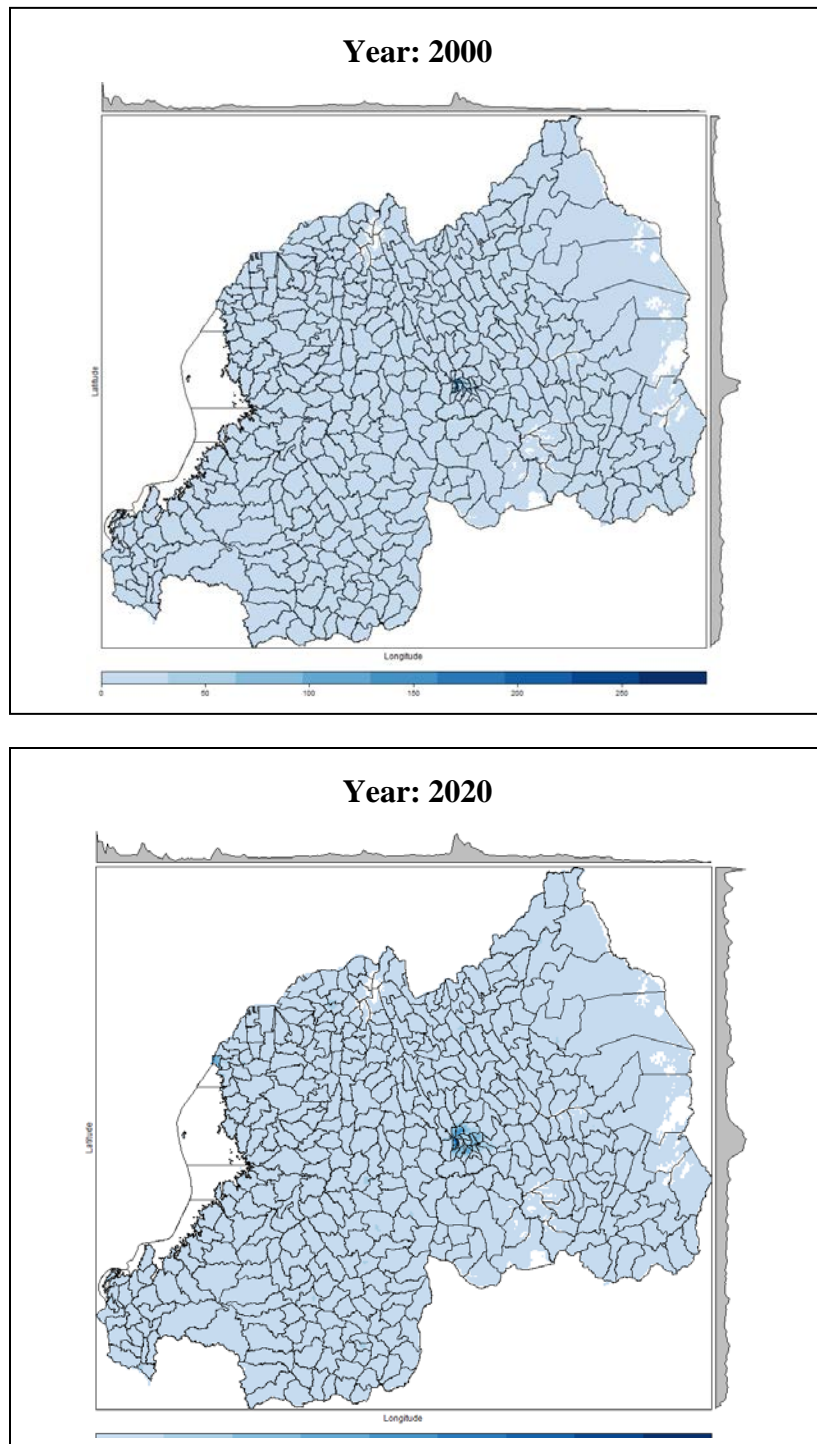


Sources: GADM database and authors' calculations.

2. **We next include population information to obtain population density in each administrative region.** For each administrative area, we translate the pixel colors to the appropriate numbers, sum these and then adjust the total sum to match the actual population data from the medium-variant United Nations statistics. We assume no change in administrative boundaries and perform the identical analysis using WorldPop pictures for 2000, 2010, and 2020. We observe an increasing population trend (intensifying pixel colors) as well as a gradual migration of population towards urban areas, specifically to Kigali, in the last two decades (Figure A2).

<sup>1</sup> Such maps for the rest of SSA countries is available in the Online Appendix.

<sup>2</sup> The colors in the map denote the boundaries of the administrative areas. Color intensities do not have carry further information.

**Figure A.III.2. Rwanda: Population in Administrative Areas**

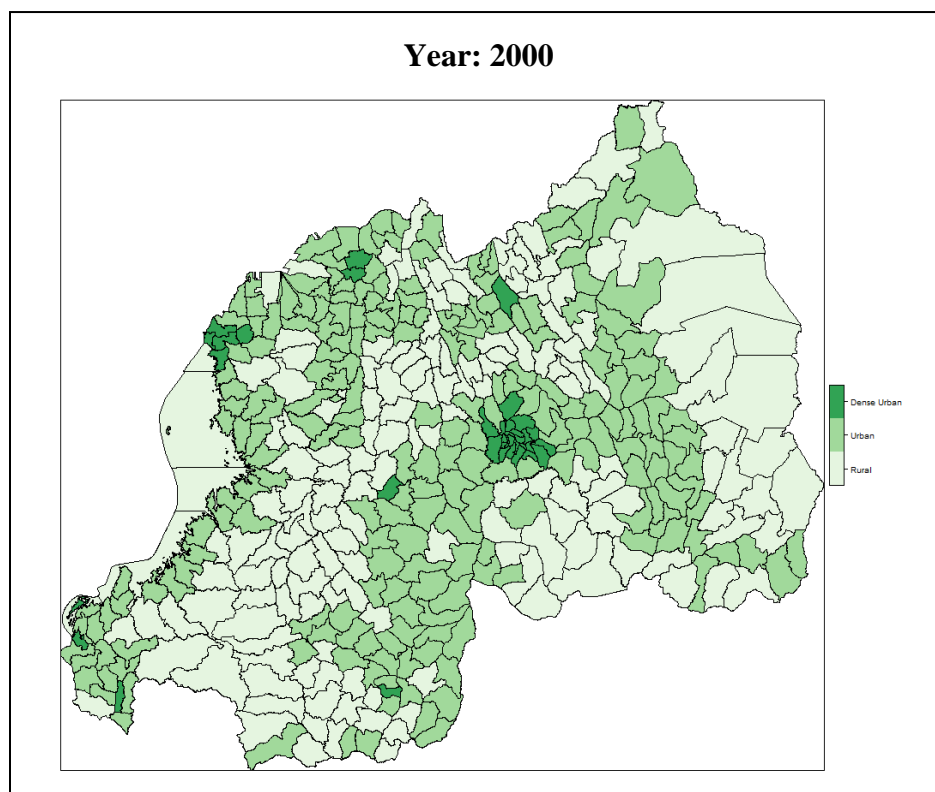
Sources: GADM and WorldPop database and authors' calculations.



3. We next project population densities for each region in 2025 and 2040 through Lagrange polynomials fitted to 2000, 2010, and 2020 weights. We observe an even faster pace of urbanization in the surrounding arounds of the province of Kigali City, particularly after taking into consideration the Kigali Innovation City: a technology cluster and a special economic zone, designed to serve as the homeland for the tech incubators, universities and both local and international companies, enjoying the preferential income tax rates.

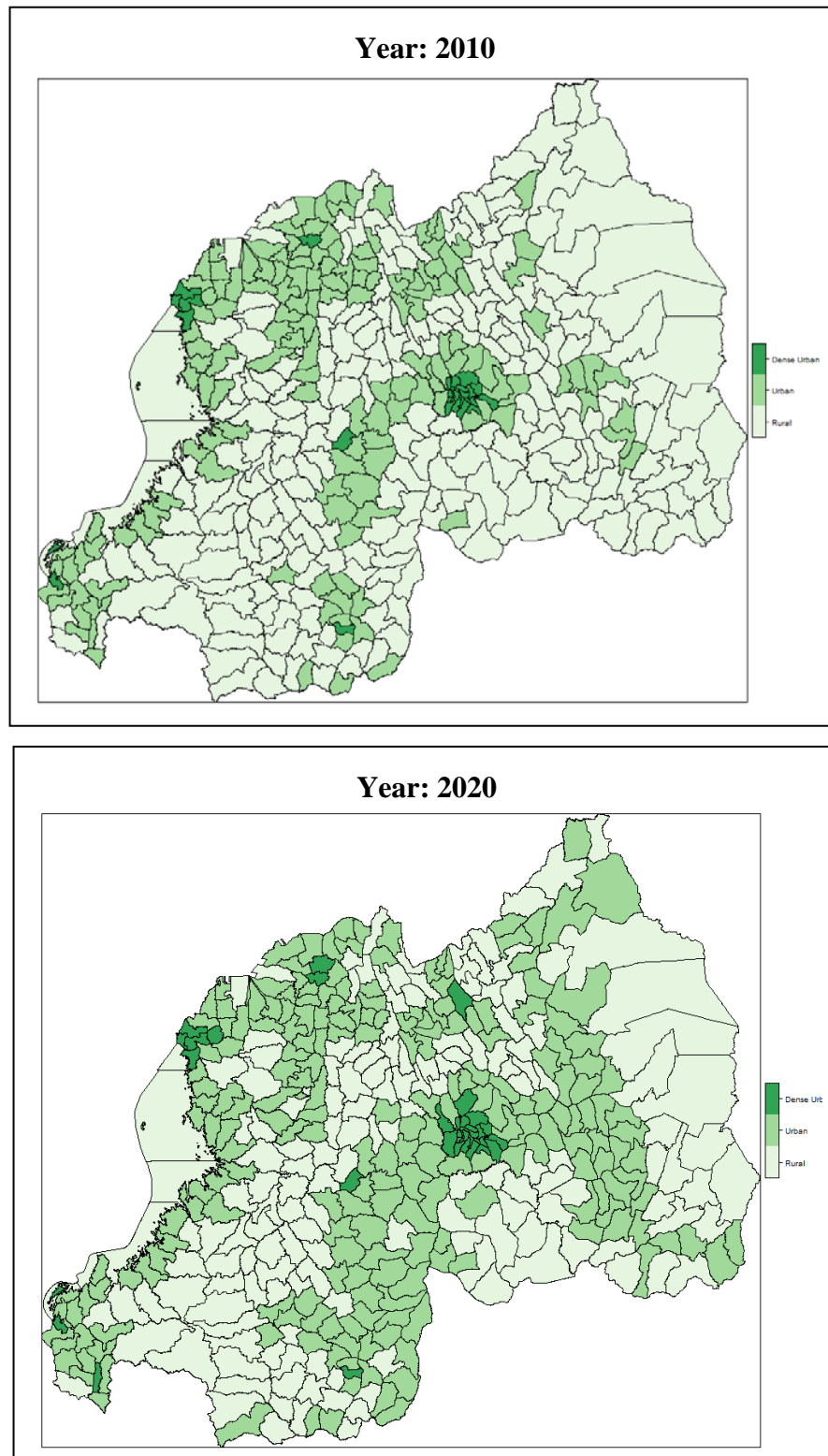
4. We next categorize the regions into three groups: *Rural*, *Urban*, or *Dense Urban*. An administrative area is designated as *Rural* when its population density is less than 500 people per square kilometer; *Urban* when the population density is greater than 500, but less than 1,500 people per square kilometers; and finally, an administrative area is designated as *Dense Urban* when the population density exceeds 1,500 people per square kilometer. An illustrative example for year 2040 is in Figures A3 and A4.<sup>3</sup>

**Figure A.III.3. Population Densities in Rwanda**



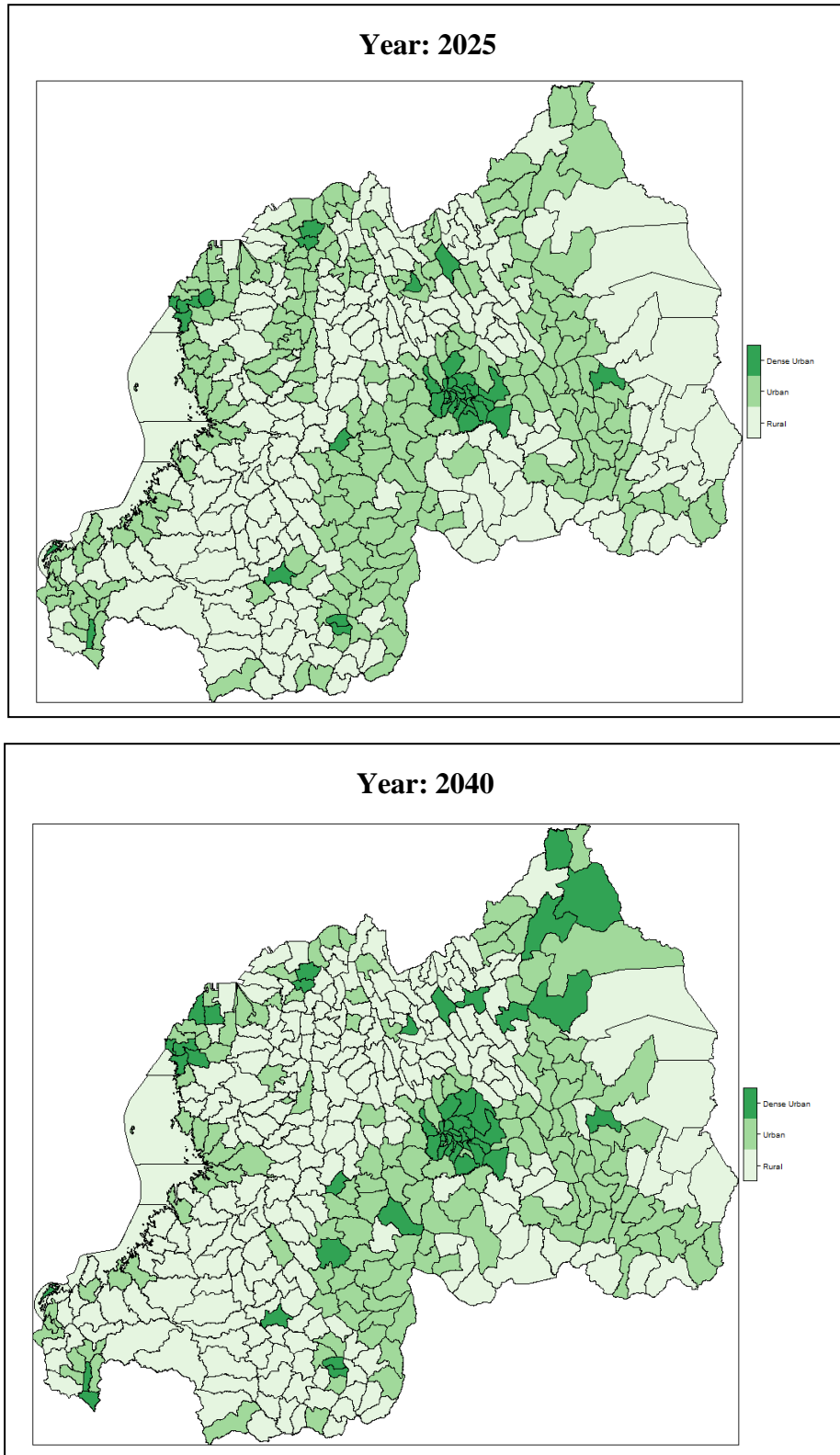
Sources: GADM and WorldPop database and authors' calculations.

<sup>3</sup> Jedwab and others (2019) argue that population density is not necessarily a satisfactory measure of urbanization and city size. Replication of this exercise, by including regional income or the level of urban technology when such data is available could be a valuable extension of this paper.

**Figure A.III.3 (Continued). Population Densities in Rwanda**

Sources: GADM and WorldPop database and authors' calculations.

**Figure AIII.4. Projected Population Densities in Rwanda**



Sources: GADM and WorldPop database and authors' calculations.

**APPENDIX IV-A. Total Capital Expenditures**  
(Millions of USD)

ISO	2025 Ericsson	2025 GSMA	2040 Ericsson	2040 GSMA	2040 Ericsson (decreased radius)	2040 GSMA (decreased radius)
AGO	551.89	545.34	1000.27	997.00	2541.72	2538.45
BDI	947.30	946.13	759.68	759.10	802.79	802.21
BEN	60.89	59.99	256.09	255.64	306.77	306.33
BFA	237.65	237.50	446.88	446.80	655.80	655.72
BWA	57.06	57.06	315.51	315.51	315.51	986.34
CAF	185.51	185.51	349.36	349.36	1089.61	1089.61
CIV	97.20	97.20	531.01	531.01	701.69	701.69
CMR	309.76	309.18	595.84	595.55	1085.36	1085.07
COD	828.89	827.79	2500.56	2500.00	4282.21	4281.66
COG	106.25	106.25	301.65	301.65	598.63	598.63
COM	6.40	6.09	22.03	21.87	21.78	21.62
CPV	2.89	2.89	12.23	12.23	14.41	14.41
ERI	47.30	47.19	101.90	101.84	190.02	189.97
ETH	812.98	801.68	2438.88	2433.23	3148.80	3143.15
GAB	4.91	4.91	164.64	164.64	450.14	450.14
GHA	134.49	132.43	539.26	538.23	701.69	700.66
GIN	192.41	191.83	317.36	317.07	583.20	582.91
GMB	24.57	24.57	48.15	48.15	55.70	55.70
GNB	18.62	18.62	41.14	41.14	63.20	63.20
GNQ	21.59	21.59	39.06	39.06	65.49	65.49
KEN	673.40	665.74	1149.99	1146.31	1798.51	1794.83
LBR	139.95	139.95	152.80	152.80	258.87	258.87
LSO	2.34	2.34	34.49	34.49	54.11	54.11
MDG	178.41	178.41	620.53	620.53	1175.78	1175.78
MLI	462.09	461.30	900.00	899.60	2302.31	2301.91
MOZ	439.96	439.17	880.50	880.11	1643.16	1642.76
MUS	1.10	0.99	22.01	21.96	22.81	22.76
MWI	963.60	962.97	1100.35	1100.03	1174.97	1174.65
NAM	158.85	158.80	470.38	470.36	1446.56	1446.54
NER	403.42	402.95	986.22	985.99	2305.44	2305.20
NGA	1083.07	1072.62	3850.62	3845.40	4986.14	4980.91
RWA	26.51	25.98	279.00	278.73	287.78	287.51
SEN	93.63	91.57	330.44	329.41	473.57	472.54
SLE	83.77	83.61	145.81	145.73	190.83	190.75
SSD	163.61	163.61	458.25	458.25	1118.99	1118.99
STP	3.42	3.42	4.41	4.41	4.53	4.53
SWZ	19.78	19.78	29.99	29.99	45.41	45.41
SYC	1.04	1.04	6.96	6.96	7.27	7.27
TCO	366.20	366.20	852.24	852.24	2254.47	2254.47
TGO	29.72	29.56	115.25	115.17	141.37	141.29
TZA	1677.96	1674.69	2266.60	2264.96	3256.28	3254.64
UGA	443.90	439.94	826.73	824.75	1033.79	1031.81
ZAF	148.24	148.24	1470.50	1470.50	2599.18	2599.18
ZMB	137.16	137.16	568.50	568.50	1360.33	1360.33
ZWE	97.34	97.34	369.29	369.29	739.85	739.85

Sources: GADM and WorldPop database and authors' calculations.

**APPENDIX IV-B. Annual Capital Expenditures**  
(Percent of GDP)

ISO	2025 Ericsson	2025 GSMA	2040 Ericsson	2040 GSMA	2040 Ericsson (decreased radius)	2040 GSMA (decreased radius)
AGO	0.03%	0.03%	0.01%	0.01%	0.03%	0.03%
BDI	1.56%	1.56%	0.19%	0.19%	0.20%	0.20%
BEN	0.02%	0.02%	0.01%	0.01%	0.01%	0.01%
BFA	0.06%	0.06%	0.02%	0.02%	0.03%	0.03%
BWA	0.01%	0.01%	0.01%	0.01%	0.04%	0.04%
CAF	0.55%	0.55%	0.25%	0.25%	0.78%	0.78%
CIV	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
CMR	0.03%	0.03%	0.01%	0.01%	0.02%	0.02%
COD	0.12%	0.12%	0.08%	0.08%	0.14%	0.14%
COG	0.05%	0.05%	0.03%	0.03%	0.07%	0.07%
COM	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%
CPV	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
ERI	0.05%	0.05%	0.03%	0.03%	0.06%	0.06%
ETH	0.03%	0.03%	0.02%	0.02%	0.02%	0.02%
GAB	0.00%	0.00%	0.01%	0.01%	0.02%	0.02%
GHA	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
GIN	0.06%	0.06%	0.02%	0.02%	0.04%	0.04%
GMB	0.04%	0.04%	0.02%	0.02%	0.02%	0.02%
GNB	0.06%	0.06%	0.02%	0.02%	0.04%	0.04%
GNQ	0.01%	0.01%	0.01%	0.01%	0.02%	0.02%
KEN	0.04%	0.04%	0.01%	0.01%	0.02%	0.02%
LBR	0.30%	0.30%	0.07%	0.07%	0.12%	0.12%
LSO	0.00%	0.00%	0.02%	0.02%	0.02%	0.02%
MDG	0.04%	0.04%	0.03%	0.03%	0.06%	0.06%
MLI	0.11%	0.11%	0.04%	0.04%	0.11%	0.11%
MOZ	0.09%	0.09%	0.04%	0.04%	0.07%	0.07%
MUS	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
MWI	0.41%	0.41%	0.07%	0.07%	0.08%	0.08%
NAM	0.07%	0.07%	0.04%	0.04%	0.12%	0.12%
NER	0.15%	0.15%	0.06%	0.06%	0.15%	0.15%
NGA	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
RWA	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
SEN	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
SLE	0.07%	0.07%	0.02%	0.02%	0.03%	0.03%
SSD	0.08%	0.08%	0.06%	0.06%	0.14%	0.14%
STP	0.05%	0.05%	0.01%	0.01%	0.01%	0.01%
SWZ	0.02%	0.02%	0.01%	0.01%	0.01%	0.01%
SYC	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TCD	0.13%	0.13%	0.08%	0.08%	0.21%	0.21%
TGO	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%
TZA	0.09%	0.09%	0.03%	0.03%	0.04%	0.04%
UGA	0.04%	0.04%	0.01%	0.01%	0.02%	0.02%
ZAF	0.00%	0.00%	0.01%	0.01%	0.01%	0.01%
ZMB	0.02%	0.02%	0.02%	0.02%	0.05%	0.05%
ZWE	0.03%	0.03%	0.03%	0.03%	0.06%	0.06%

Sources: GADM and WorldPop database and authors' calculations.

**APPENDIX IV-C. Operational Expenditures**  
(Millions of USD)

ISO	2020	2025 Ericsson	2025 GSMA	2040	2040 (decreased radius)
AGO	0.78	9.83	9.80	9.25	14.25
BDI	4.78	43.46	43.45	44.12	44.26
BEN	0.90	2.39	2.37	4.55	4.12
BFA	0.00	7.75	7.74	12.54	12.38
BWA	1.54	2.37	2.37	0.60	7.97
CAF	0.00	2.22	2.22	0.92	6.42
CIV	1.50	3.21	3.21	6.81	5.92
CMR	0.06	7.91	7.91	9.85	13.19
COD	0.00	8.43	8.42	17.17	20.02
COG	0.07	1.43	1.43	2.35	3.32
COM	0.06	0.22	0.21	0.10	0.32
CPV	0.32	0.43	0.43	0.53	0.51
ERI	0.00	1.20	1.20	1.85	2.32
ETH	1.21	12.84	12.80	16.14	16.79
GAB	1.61	1.71	1.71	1.36	5.04
GHA	1.53	4.93	4.89	9.25	9.92
GIN	0.71	6.94	6.93	7.40	10.69
GMB	0.00	0.79	0.79	1.13	1.10
GNB	0.17	0.82	0.82	1.31	1.34
GNQ	0.00	0.66	0.66	0.75	1.04
KEN	7.11	29.74	29.58	30.27	39.86
LBR	0.28	6.26	6.26	6.98	9.12
LSO	0.20	0.25	0.25	0.60	0.54
MDG	1.00	4.34	4.34	6.43	11.30
MLI	0.00	8.77	8.76	6.62	20.76
MOZ	0.00	9.10	9.10	10.73	14.97
MUS	0.31	0.34	0.34	0.32	0.38
MWI	15.19	51.38	51.38	51.70	52.28
NAM	1.67	4.28	4.28	1.91	11.91
NER	0.00	8.03	8.02	10.12	25.43
NGA	11.26	28.38	28.26	24.67	44.71
RWA	6.65	7.50	7.49	7.80	8.11
SEN	0.64	3.05	3.02	5.74	6.22
SLE	0.00	2.95	2.95	4.74	4.17
SSD	0.39	3.90	3.90	4.48	13.79
STP	0.00	0.13	0.13	0.17	0.15
SWZ	0.20	0.95	0.95	1.11	1.18
SYC	0.41	0.45	0.45	0.45	0.46
TCD	2.57	11.66	11.66	9.75	29.34
TGO	0.00	0.66	0.66	2.52	1.58
TZA	7.99	63.83	63.79	64.19	73.71
UGA	3.03	18.06	18.01	23.59	22.81
ZAF	8.61	11.09	11.09	11.37	23.00
ZMB	0.87	2.00	2.00	2.28	4.47
ZWE	0.78	2.25	2.25	2.95	5.49

Sources: GADM and WorldPop database and authors' calculations.

**APPENDIX IV-D. Operational Expenditures**  
(Percent of GDP)

ISO	2020	2025 Ericsson	2025 GSMA	2040	2040 (decreased radius)
AGO	0.00%	0.00%	0.00%	0.00%	0.00%
BDI	0.06%	0.43%	0.43%	0.16%	0.16%
BEN	0.00%	0.00%	0.00%	0.00%	0.00%
BFA	0.00%	0.01%	0.01%	0.01%	0.01%
BWA	0.00%	0.00%	0.00%	0.00%	0.00%
CAF	0.00%	0.04%	0.04%	0.01%	0.07%
CIV	0.00%	0.00%	0.00%	0.00%	0.00%
CMR	0.00%	0.01%	0.01%	0.00%	0.00%
COD	0.00%	0.01%	0.01%	0.01%	0.01%
COG	0.00%	0.00%	0.00%	0.00%	0.01%
COM	0.00%	0.01%	0.01%	0.00%	0.01%
CPV	0.01%	0.01%	0.01%	0.00%	0.00%
ERI	0.00%	0.01%	0.01%	0.01%	0.01%
ETH	0.00%	0.00%	0.00%	0.00%	0.00%
GAB	0.00%	0.00%	0.00%	0.00%	0.00%
GHA	0.00%	0.00%	0.00%	0.00%	0.00%
GIN	0.00%	0.01%	0.01%	0.01%	0.01%
GMB	0.00%	0.01%	0.01%	0.01%	0.01%
GNB	0.00%	0.02%	0.02%	0.01%	0.01%
GNQ	0.00%	0.00%	0.00%	0.00%	0.00%
KEN	0.00%	0.01%	0.01%	0.00%	0.01%
LBR	0.00%	0.08%	0.08%	0.05%	0.06%
LSO	0.00%	0.00%	0.00%	0.00%	0.00%
MDG	0.00%	0.01%	0.01%	0.00%	0.01%
MLI	0.00%	0.01%	0.01%	0.00%	0.01%
MOZ	0.00%	0.01%	0.01%	0.01%	0.01%
MUS	0.00%	0.00%	0.00%	0.00%	0.00%
MWI	0.06%	0.13%	0.13%	0.05%	0.05%
NAM	0.01%	0.01%	0.01%	0.00%	0.02%
NER	0.00%	0.02%	0.02%	0.01%	0.02%
NGA	0.00%	0.00%	0.00%	0.00%	0.00%
RWA	0.02%	0.01%	0.01%	0.01%	0.01%
SEN	0.00%	0.00%	0.00%	0.00%	0.00%
SLE	0.00%	0.02%	0.02%	0.01%	0.01%
SSD	0.00%	0.01%	0.01%	0.01%	0.03%
STP	0.00%	0.01%	0.01%	0.01%	0.01%
SWZ	0.00%	0.01%	0.01%	0.00%	0.00%
SYC	0.01%	0.01%	0.01%	0.00%	0.00%
TCD	0.01%	0.03%	0.03%	0.01%	0.04%
TGO	0.00%	0.00%	0.00%	0.01%	0.00%
TZA	0.00%	0.02%	0.02%	0.01%	0.01%
UGA	0.00%	0.01%	0.01%	0.01%	0.01%
ZAF	0.00%	0.00%	0.00%	0.00%	0.00%
ZMB	0.00%	0.00%	0.00%	0.00%	0.00%
ZWE	0.00%	0.00%	0.00%	0.00%	0.01%

Sources: GADM and WorldPop database and authors' calculations.

**APPENDIX V. Total Cost per Subscriber**  
(Percent of income per capita)

ISO	4G	5G
AGO	8.66	4.81
BDI	451.08	43.58
BEN	4.06	2.89
BFA	16.80	6.57
BWA	2.17	4.85
CAF	226.62	221.13
CIV	1.84	1.77
CMR	8.43	3.66
COD	40.99	33.96
COG	7.15	7.46
COM	18.52	8.31
CPV	2.05	1.25
ERI	49.14	29.60
ETH	7.95	2.81
GAB	0.54	2.44
GHA	1.29	1.12
GIN	16.60	8.08
GMB	7.16	2.87
GNB	18.64	10.03
GNQ	2.87	2.76
KEN	5.85	2.35
LBR	101.40	38.09
LSO	0.89	2.98
MDG	17.45	17.26
MLI	19.22	15.52
MOZ	17.64	10.25
MUS	0.13	0.18
MWI	150.31	19.03
NAM	14.79	18.06
NER	64.07	51.05
NGA	2.80	2.02
RWA	3.15	1.98
SEN	3.02	2.37
SLE	20.30	7.68
SSD	42.81	39.59
STP	9.27	2.01
SWZ	4.28	1.64
SYC	1.69	1.00
TCD	224.43	239.56
TGO	6.28	4.42
TZA	19.75	5.25
UGA	9.78	2.43
ZAF	0.42	1.16
ZMB	3.93	5.26
ZWE	4.54	7.60

Sources: GADM and WorldPop database and authors' calculations.