Policy Research Working Paper 10263

Policy Options for Broadband Infrastructure Strategies

A Simulation Model for Affordable Universal Broadband in Africa

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WORLD BANK GROUP
Digital Development Global Practice
December 2022

Policy Research Working Paper 10263

Abstract

Goal 9 of the Sustainable Development Goals aims to provide universal affordable broadband globally by 2030. However, a lack of data, combined with few independent and scientifically reproducible assessments, makes it challenging for governments to make strategic choices to achieve this target. Therefore, new research approaches are required to support decision evaluation. This paper demonstrates an innovative method that addresses data and model uncertainty by developing open-source software to explore affordable universal broadband strategies, using a scenario-based hypothetical mobile operator. Targets being considered by the United Nations' Broadband Commission are evaluated, with the financial costs of different infrastructure decisions quantified for the whole of Africa. The results suggest that "leapfrogging" to 4G is more cost efficient than 3G for providing universal broadband, with savings between 7 and 57 percent for 10 gigabytes per month and between 20 and 47 percent for 30 gigabytes per month. Moreover, the cost of connecting all unconnected and underserved users across Africa can be reduced by approximately 40 percent by targeting a per user consumption rate of 10 gigabytes per month, compared to 30 gigabytes per month. Future research should also aim to consider demand-side impacts, for example, how device affordability may affect adoption.

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Policy Options for Broadband Infrastructure Strategies: A Simulation Model for Affordable Universal Broadband in Africa

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JEL Classification

L5 Regulation and Industrial Policy; L96 Telecommunications

Key words

Policy, broadband, universal service, 4G, infrastructure.

Acknowledgments

The research was supported under the Effective Regulation for Digital Development program, supported by the Digital Development Partnership administered by the World Bank. The author would like to thank multiple colleagues for their review feedback, including Tania Begazo, Moussa Blimpo, Mark A. Dutz, Izak Atiyas, Toker Doganoglu, Vivien Foster, Justice Tei Mensah, and Timothy Kelly. This paper was presented at the World Bank Africa Series Seminar in March 2021. Additionally, a conference version of this paper was recognized with the Benton Early Career Scholar Award at TPRC48. Finally, the author would like to thank the governments of Senegal and Kenya for site location data.

1. Introduction

Broadband has long been recognized as critical for helping to deliver the Sustainable Development Goals (SDGs) and enable digitally led development. Indeed, governments are increasingly treating broadband infrastructure on par with energy or water access, given its importance for economic development (Chen et al., 2020; Czernich et al., 2011; Greenstein and McDevitt, 2011; Koutroumpis, 2009; Oughton et al., 2015; Röller and Waverman, 2001). Even basic broadband transforms the opportunities available to citizens (Aker, 2011; Aker and Blumenstock, 2015; Aker and Mbiti, 2010; Suri and Jack, 2016). For example, empirical evidence for internet deployment in Africa suggests the probability that an individual is employed substantially increases by approximately 7%-13% when broadband connectivity becomes available (Hjort and Poulsen, 2019).

Over 3 billion people are connected globally to the internet via cellular, leaving a significant digital divide (50%). Approximately 40% of people live within cell coverage but without a handset ('the usage gap'), while the remaining 10% of people live without coverage ('the coverage gap') (GSMA, 2019a). Currently the ITU has set a range of targets to be achieved by 2025 for internet access globally (International Telecommunication Union, 2019), including bringing 75% of the global population online by 2025. The United Nations (UN) Broadband Commission has been exploring the implications of different universal service targets, but hitherto there has been only a limited number of studies quantifying the level of investment involved.

Understanding the economics of internet infrastructure is essential (Claffy and Clark, 2019; Greenstein, 2020; Villapol et al., 2018; Wang and Dang, 2019). Despite high-level policy ambitions, how universal broadband should be delivered globally is still under researched. Whereas universal service has been a cornerstone of regulatory policy in networked industries for many decades in high-income economies (Cremer et al., 2001), greater emphasis is now being placed on this concept in emerging economies for broadband. Indeed, research has shown that the requirement to serve rural areas with cell phone coverage may lower operator profits but provide substantial increases in net social welfare (Björkegren, 2019), justifying the wider benefits of universal access.

Although there are still many broadband issues in high-income countries, new universal service policies have helped introduce greater market-based competition into traditional monopoly industries, where delivery was previously achieved via nationalization. Yet, in emerging economies most assets need to be built from scratch, requiring considerable investment (Cavalcante et al., 2021). Therefore, existing market policies may struggle to achieve universal service, potentially requiring government market intervention, for example, via state subsidies. Governments also need to consider how different technologies and infrastructure sharing policies could reduce deployment costs, lowering the quantity of state subsidies required.

Two research questions are therefore identified for investigation including:

1. Which technologies and infrastructure sharing policies should governments encourage to enable universal broadband?
2. What magnitude of investment is required for universal broadband across the African continent, to achieve SDG Target 9c?

Having outlined these research questions, a literature review is now undertaken before a suitable method is described in Section 3. The assessment results will then be presented in Section 4, with the results evaluated in Section 5, and the paper conclusions reported in Section 6.

2. Reviewing universal broadband strategies

Universal service is defined as an operator providing a basic level of service to all potential users at an affordable rate. This paper focuses on providing 'basic broadband' (for example, a mobile broadband service enabling 10-30 GB/Month of user traffic with an approximate mean speed of 10 Mbps). There are three main types of broadband technologies which are potential candidates, including fixed access (via a copper, coaxial or fiber cable), wireless access (via cellular, Wi-Fi or satellite), or fixed wireless access (a hybrid approach). However, even within these segments there are competing options, such as the competition between cellular versus Wi-Fi for wireless broadband connectivity (Oughton et al., 2021). Each technology exhibits a different cost supply curve, making it more competitive in different deployment situations (Anusha et al., 2017), depending on the necessary capacity and coverage required in a local area. For example, in dense urban areas where traffic demand is very high, fixed fiber is much more economic than using wireless methods. In contrast, wireless access is much more economic in low density areas where there are fewer users, spread out over a wide area (Hameed et al., 2018; Lertsinsrubtavee et al., 2018), particularly as the initial capital investment can be lower. A variety of new technologies have been proposed for helping to fill coverage gaps in rural and remote areas (Heimann et al., 2019). These range from incremental extensions of existing technologies, such as larger cells or using TV whitespaces (Khalil et al., 2017), to much more radical developments, ranging from Unmanned Aerial Vehicles (Chiaraviglio et al., 2019, 2017; Jiménez et al., 2018), to deploying mass produced Low Earth Orbit (LEO) satellite constellations (del Portillo et al., 2021; Saeed et al., 2020).

Backhaul connectivity remains one of the key challenges for serving remote locations, as new local access technologies need to be able to transport data to and from servers elsewhere in the internet (Borralho et al., 2021; Jaber et al., 2016). The costs of this data transportation are prohibitive in many locations, especially in mountainous areas where many line-of-sight connections could be required. Wireless backhaul links are generally preferred for terrestrial deployments in hard-to-reach areas. However, the civil engineering costs of erecting towers with line-of-sight paths can be high, particularly when deploying in challenging environments.

Broadband connectivity is increasingly seen as a merit good because of the large number of benefits which can accrue to both users and the wider economy. In locations where the costs of delivery exceed the potential revenue a Mobile Network Operator (MNO) could achieve, market failure can occur holding back necessary infrastructure investment. In such a situation, appropriate regional or national policy measures can be taken to encourage greater economic viability in the delivery of universal broadband. Supply-side cost reducing measures are a common target to overcome market failure in rural and remote areas, therefore one such approach focuses on the sharing of passive (non-electronic) and/or active (electronic) infrastructure assets (Cavalcante et al., 2021; Faisal et al., 2022; Gedel and Nwulu, 2021; Heimerl et al., 2013; Koratagere Anantha Kumar and Oughton, 2022; Lähteenmäki, 2021; Latapu et al., 2018; Lehr et al., 2021; Maule et al., 2021; Oughton et al., 2018; Sanguanpuak et al., 2018; Yamajo, 2022), particularly in emerging markets (Meddour et al., 2011). There has been less of a need to share infrastructure in earlier generations, such as during the 2G era, as MNOs experienced increasing revenues and benefited from very large cell areas. Currently however, revenues are either static or declining in many global telecommunication markets (GSMA, 2020). There are multiple types of infrastructure sharing, with passive approaches focusing on civil engineering infrastructure such as the site compound and tower, whereas active approaches focus on the Radio Access Network (RAN).

Sharing active equipment has a beneficial impact on lowering operational expenses such as energy consumption (Antonopoulos et al., 2015; Bousia et al., 2016; Dlamini and Vilakati, 2021), particularly in areas with low demand where assets are not close to their full capacity. Although there has been interest in infrastructure sharing in Sub-Saharan Africa (Marino Garcia and Kelly, 2015), fewer than 10 of the 98 countries which have implemented active sharing agreements are on the African continent (McKinsey & Company, 2018). Spectrum sharing strategies introduce efficiency benefits, such as coordinating interference and providing carrier aggregation, reducing the number of required sites, using spectrum more efficiently and improving economic viability (Boulos et al., 2020; Frias et al., 2020; Gomez et al., 2019; Jurdi et al., 2018; Peha, 2009). Moreover, network resource sharing helps to expedite the time taken to achieve viability for greenfield infrastructure, which is essential for reaching rural and remote areas (Mamushiane et al., 2018). Such cost saving measures can help to reduce prices for consumers in low and middle income countries across Africa, boosting adoption (International Finance Corporation, 2021).

However, a key caveat is that infrastructure sharing benefits need to be traded-off against any potential negative impacts (Oughton et al., 2022b; Sanguanpuak et al., 2019). For example, infrastructure competition is known to produce positive consumer outcomes, therefore consolidation needs to be assessed in terms of how it affects dynamic competition (Wallsten, 2005, 2001; Yoo, 2017). Governments set the 'rules of the game' for telecom markets, affecting the level of market concentration, competition and prices, and generally pro-competition policies have been found to reduce prices, but not necessarily services or investment (Faccio and Zingales, 2017). In highly unviable locations, one option is to utilize active infrastructure sharing only in these areas, such as via a shared rural network (SRN), while preserving the benefits of competition in viable areas (mainly urban and suburban locations). For example, such an approach has been introduced in Tanzania, which is one of the first active infrastructure sharing initiatives in East Africa (GSMA, 2016). However, it is more common to see passive infrastructure sharing in African countries, with examples being tower sharing in Zambia and the Republic of Congo, or cross-sector sharing in Zambia between electricity and telecommunications (Saif et al., 2021; Strusani and Houngbonon, 2020).

Where market failure cannot be addressed via cost-reducing infrastructure sharing policies, governments may look to use public subsidies to provide financial support for broadband infrastructure deployment (Boik, 2017). However, evaluation of the effectiveness of broadband subsidies is currently ongoing. Recent work has found that subsidies have been effective in closing the digital divide, but have not necessarily led to job creation (as least in the European Union) (Briglauer et al., 2019). But, subsidies are often associated with higher levels of broadband coverage, indicating public investment takes over from private investment (Bourreau et al., 2020). Assessment finds that the indirect economic benefits from broadband in GDP terms, outweigh past funding expenses arising from subsidy programs (Briglauer et al., 2021). However, other studies find that subsidies to boost broadband availability do not increase adoption (Rosston and Wallsten, 2020) or lead to improved educational results (Hazlett et al., 2019).

2.1. Reviewing universal broadband assessments

Previous assessments of universal broadband have focused mainly on the infrastructure costs of delivery. As identified in the introduction, the 'Connecting Humanity' assessment by the International Telecommunication Union (ITU) focuses on deploying ~10 Mbps broadband to 90% of the global population over 10 years of age, producing an investment estimate of US$ 428 billion (International Telecommunication Union, 2020). However, there are many caveats and assumptions associated with this estimate. For example, Quality of service is not explicitly considered in this analysis, meaning there is no guarantee that the ~10 Mbps broadband target can be maintained in peak periods. Moreover, the amount estimated by the ITU mainly covers capital and operational expenditure (with a small quantity for contents, skills, and regulation), but does not adopt a full-balance sheet approach to account for user cross-subsidization (which is essential to estimate where short-falls occur, and necessary public subsidies are required). Additionally, questions remain around the economic viability of satellite services being able to support very high adoption (e.g., up to 90%) in certain areas.

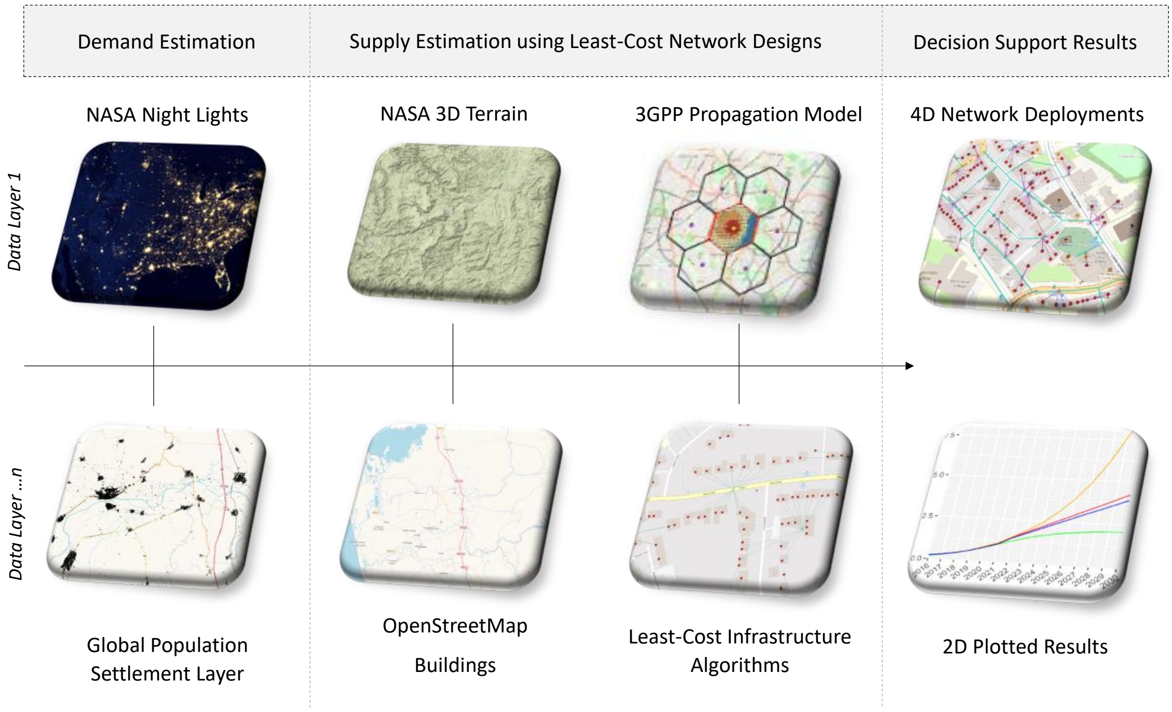
A contrasting assessment by the World Bank which does include quality of service suggests the private and public cost of universal broadband could be ~$2 trillion to achieve at least ~10 Mbps universal broadband in low and middle income countries (LMICs), equating to investment of more than 0.67% of annual GDP over the next decade (Oughton et al., 2022b).

Building on the ITU's global analysis, the United Nation's states that 1.1 billion new users must be connected in Africa to ~10 Mbps per user by 2030 to achieve SDG 9c, costing approximately $100 billion (Broadband Commission for Sustainable Development, 2019). This analysis anticipates that between 15%-20% of the rural population will be connecting via satellite by 2030, equating to 100 million remote rural users. However, no techno-economic modeling of the satellite sector is carried out. For example, analysis of Space X Starlink and Blue Origin Kuiper indicates that LEO constellations may need to have fewer than 1 user per 10 km^2 to provide ~10 Mbps per user in the busiest hour, with this number needing to be even lower for OneWeb (Osoro and Oughton, 2021). Indeed, the contrasting evidence presented suggests that we could be overestimating the capacity of satellite connectivity in policy strategies, meaning the cost of universal broadband deployment is being underestimated. This provides justification for focusing on universal broadband strategies based on terrestrial technologies, such as 3G and 4G. Having reviewed literature pertinent to the research questions, a method will now be presented.

3. Method

Myriad high-level policy reports have attempted to quantify the costs of infrastructure delivery for connecting (only) unconnected communities (International Telecommunication Union, 2020). The majority use high-level spreadsheet methods to estimate the required investment, leaving substantial uncertainty embedded within the results which is rarely portrayed to policy makers. The method developed here takes a new approach by drawing on a range of analytical tools rarely utilized in telecom policy research, including remote sensing and least-cost network designs, derived from infrastructure simulations. Figure 1 illustrates how these approaches are combined to produce demand and supply estimates to quantify universal broadband strategies. The open-source codebase adheres to scientific computing best practices (fully-tested and fully-documented) (Wilson et al., 2017, 2014) and is openly available from the Policy Options for Broadband Infrastructure Strategies (pobis) repository.

Figure 1 Quantifying universal broadband strategies using data analytics methods



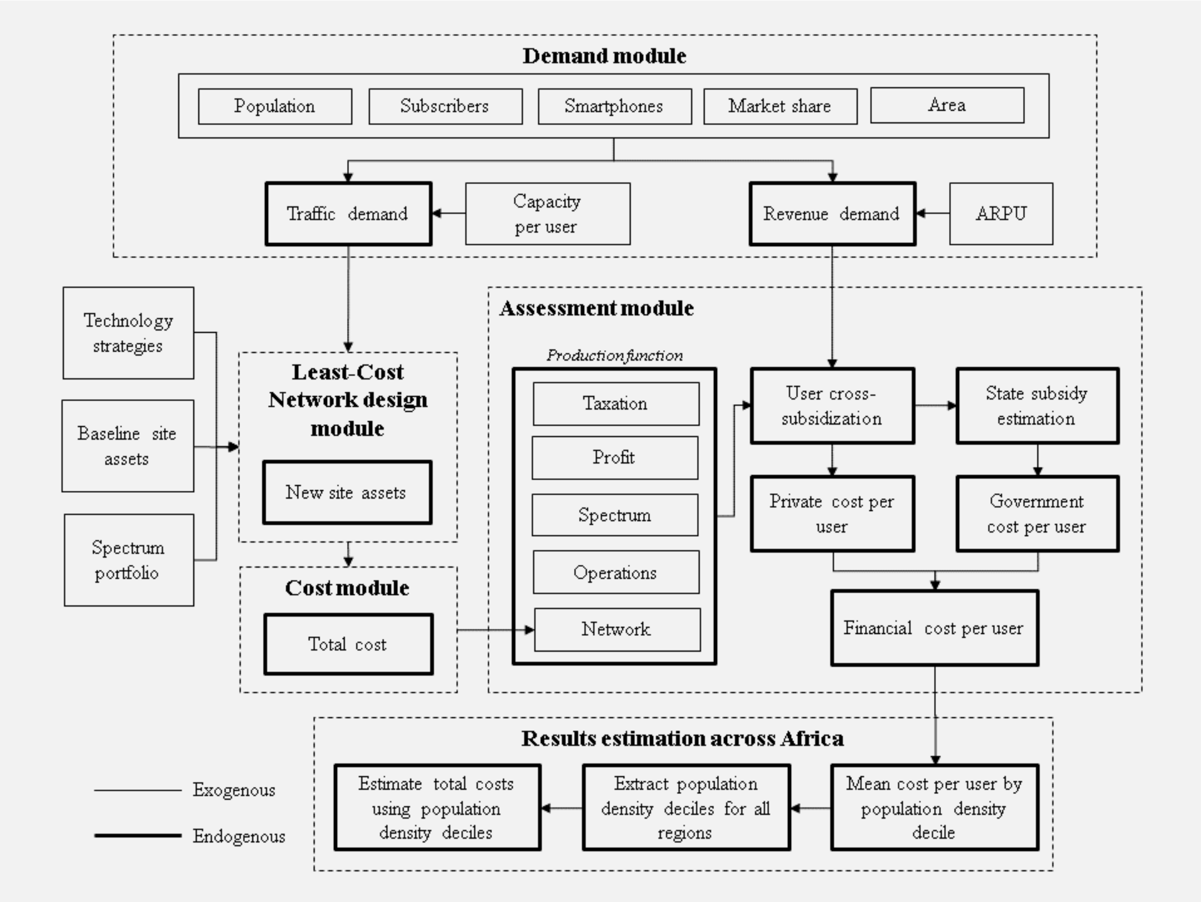
A scenario-based approach is used to assess the research questions, as is common in the literature when reliable scientific data are missing. The use of scenarios also enables ‘what if’ questions to be tested (Paltsev, 2017; Postma and Liebl, 2005; Swart et al., 2004), which is a common way to explore infrastructure decisions (Hall et al., 2016a; Oughton and Russell, 2020; Thoung et al., 2016). This involves using a standard regulatory approach for making telecom policy decisions by modeling a representative ‘*Hypothetical Mobile Network Operator*’, based on a Long-Run Incremental Cost modeling (Ofcom, 2018). The method is applied to assess six East and West African countries over the next decade (Côte d’Ivoire, Mali, Senegal, Kenya, Tanzania, and Uganda), justified based on their socio-economic contexts being broadly representative of Sub-Saharan Africa, as demonstrated comparatively in Table 1.

Table 1 Comparison of key country metrics

Country	Côte d'Ivoire	Mali	Senegal	Kenya	Tanzania	Uganda	Source
Population (m)	25	19	16	51	56	43	(WorldPop, 2019)
Rural Population	49%	58%	53%	73%	66%	76%	World Bank?
Area (km2)	318,000	1,220,190	192,530	569,140	885,800	200,520	(GADM, 2019)
Population Density (per km2)	79	16	83	90	63	214	Author calculations
GDP (US$ Bn)	43	17	24	88	58	27	(World Bank, 2022)
GDP Per Capita	USD 1715	USD 901	USD 1,522	USD 1,711	USD 1,051	USD 643	(World Bank, 2022)
Income group	Lower-middle	Low	Lower-middle	Lower-middle	Lower-middle	Low	(World Bank, 2022)
4G Population Coverage	60%	45%	75%	77%	13%	31%	(GSMA, 2020)
3G Population Coverage	72%	72%	95%	96%	66%	87%	(GSMA, 2020)
Smartphone Penetration (Urban)	36	36	36	55	36	36	(Research ICT Africa, 2018)
Smartphone Penetration (Rural)	24	8	24	17	24	8	(Research ICT Africa, 2018)

The sequential method used to obtain the results for each country is outlined in Figure 2 (reflecting the software module structure).

Figure 2 Assessment software design



3.1. Strategies

The research questions reflect the main decisions governments currently face when designing policies for universal broadband, ranging from which technologies to encourage, to the degree of infrastructure sharing desired. The research questions will be assessed for the two download capacity targets of 10 or 30 GB/month per user. For decisions around the types of technologies that could be used, the focus is placed on a cellular approach, exploring whether 3G or 4G should be deployed. Additionally, as many of the areas yet to receive a basic level of coverage are rural and often remote, the backhaul technology is a significant cost component (Ignacio et al., 2020). Wireless backhaul is likely to be cheaper, than a fixed fiber link, thanks to lower capital expenditure (capex), but fiber can serve much higher traffic demand and has lower operational expenditure (opex) over the long-term.

Different types of infrastructure sharing are to be tested, reflecting the options identified in the literature review (and illustrated in Figure S1 of the Supplementary Materials). In the baseline each MNO builds their own network to serve their market share with no sharing taking place. The other infrastructure sharing strategies include (i) passive sharing (site compounds and backhaul), (ii) active network sharing (Multi Operator Radio Access Network – MORAN) and (iii) a shared rural network (using a MORAN only in rural areas).

3.2. High-resolution spatial estimation of traffic and revenue

Two scenarios (S_t) of 10 or 30 GB per month (t) per user are selected as capable of supporting necessary data consumption for a variety of key use cases (World Bank, 2021). Before the area demand can be estimated, it is first necessary to convert from these monthly data usage amounts into a capacity per user, per second quantity (Cap_i), as specified in Equation (1).

$$Cap_i = S_t \cdot 1000 \cdot 8 \cdot \left(\frac{1}{n_d}\right) \cdot \left(\frac{BH}{100}\right) \cdot \left(\frac{1}{3600}\right) \qquad (1)$$

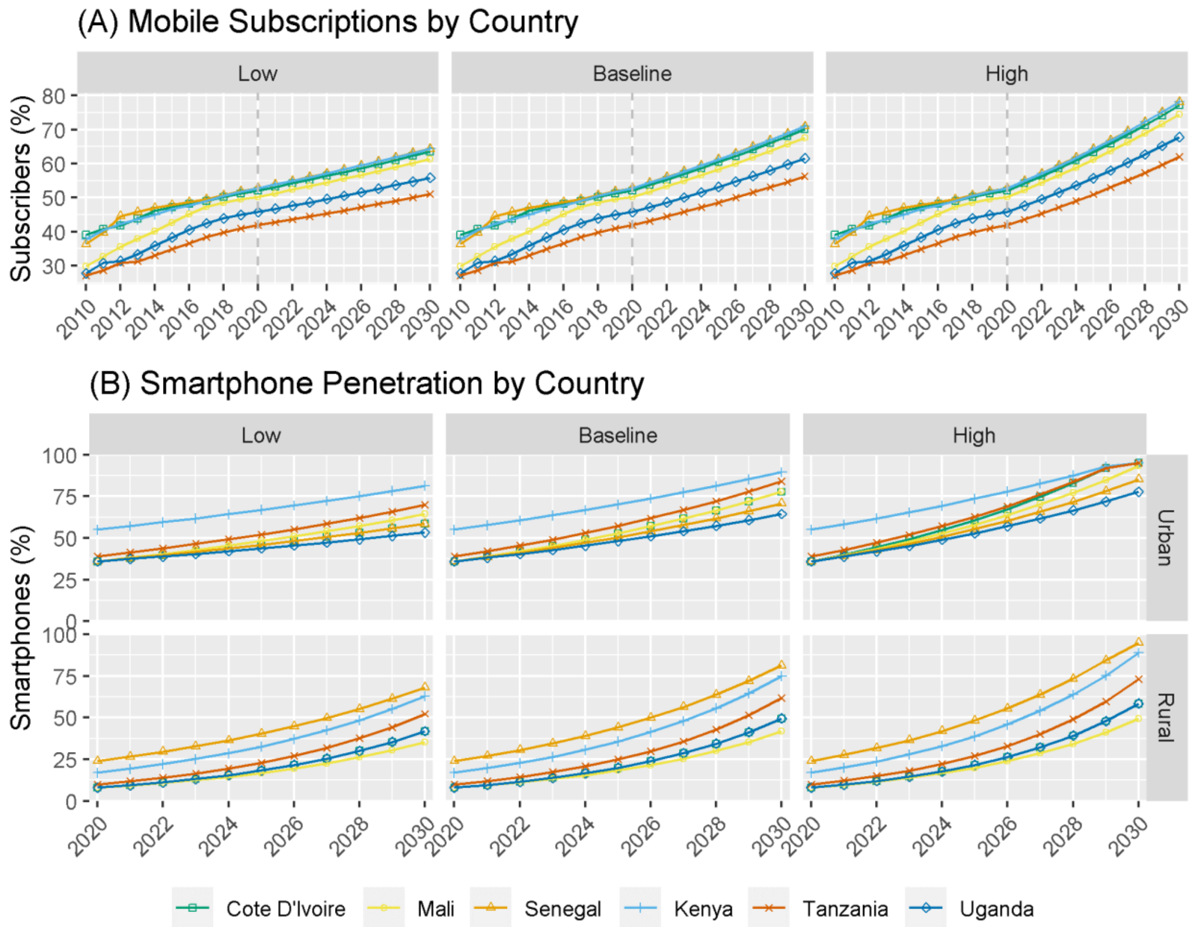
Firstly, the monthly data consumption (S_t) in gigabytes is converted into megabytes (by multiplying by 1,000), before being converted into bits (by multiplying by 8). Secondly, this quantity is converted into a daily amount by accounting for the number of days in a month (n_d) (30), and then accounting for the traffic taking place in the busiest hour of the day (BH) (15%). Finally, this hourly amount can be converted to the number of megabits per second (Mbps), given each hour has 3,600 seconds.

Next, the demand module estimates the traffic demand ($Demand_i$) (Mbps km^2) for unique local smartphone users, in the ith local region at time t, using data on the total population (Pop_i), unique cell phone penetration (Pen_{it}), unique smartphone penetration by urban-rural area ($SP_{Pen_{it}}$) and a desired per user capacity in the busiest hour of the day (Cap_i). The formula used to make this estimation is described in equation (2) and the maximum data demand for all years (2020-2030) is used to represent the peak traffic load.

$$Demand_i = \frac{Pop_i \cdot Pen_{it} \cdot SP_{Pen_{it}} \cdot Cap_i}{Market_{Share_i}} / ActiveUsers / Area_i \quad (2)$$

The population is extracted from the WorldPop 2020 global raster layer (Tatem, 2017; WorldPop, 2019), the cell phone penetration is treated as the GSMA unique number of mobile subscribers (GSMA, 2020), and the smartphone adoption rate is taken from the Research ICT Africa After Access Survey (Research ICT Africa, 2018). Metrics representing the future number of unique individuals with cell phone subscriptions and smartphones are used to ensure that demand represents the number of data-intensive users simultaneously accessing the network at once (capturing both currently unconnected *and* underserved users). The market share ($Market\_Share_i$) is exogenously stated depending on the number of MNOs present, which is treated as 3 in all countries, except Mali (where there are currently only 2 major MNOs) (Observatoire des Marches des Telecommunications, 2019). As not all users access the network simultaneously, an active user rate ($ActiveUsers$) of one-in-twenty is used (Holma and Toskala, 2011; Souza et al., 2021). Both the number of unique mobile subscribers and the smartphone adoption rate are forecast forward as a set of exogenous inputs for the simulation model based on their historical trajectory, as illustrated with the scenario trends in Figure 3. Indeed, the penetration rate growth is forecast at 2%, 3% and 4% for the low, baseline and high scenarios, respectively. The high scenario broadly aligns with SDG Target 9c, as defined by the ITU, whereby ~90% of adults adopt broadband by 2030 (International Telecommunication Union, 2020). In contrast, the baseline scenario is an optimistic continuation of the current trajectory (akin to a standard technology diffusion curve), whereas the low scenario is conservative with only modest adoption (representing an untypical technology diffusion curve).

Figure 3 Unique mobile subscribers by country



To closely match the UN Broadband Commission universal broadband definition, the initial base population in each area is classed as all those people over 10 years of age, with this demographic information extracted using WorldPop demographic data layers.

The revenue ($Revenue_i$) is estimated in a similar way for each region, except the exogenous per user capacity is substituted for the Average Revenue Per User ($ARPU_i$), as illustrated in equation (3).

$$Revenue_i = \frac{Pop_i \cdot Pen_{it} \cdot SP_{Pen_{it}} \cdot ARPU_i}{Market\_Share_i} \quad (3)$$

The monthly ARPU is estimated by remotely sensing nightlight luminosity from NASA VIIRS data, as a predictor of economic consumption in local areas, in order to allocate economic consumption tiers (e.g., for how much users can spend on broadband) (Bruederle and Hodler, 2018; Henderson et al., 2012, 2011; Oughton and Mathur, 2021). While there is uncertainty in any predictive measure, this method is preferable to selecting an aggregate approach, as has been carried out in previous policy assessments (International Telecommunication Union, 2020). Nightlight luminosity is measured in 'Digital Numbers' (DN) and the mean luminosity is used to allocate high, medium, and low consumption tiers for broadband spending (>5 DN, <5 DN and <1 DN respectively). ARPU estimates for these consumption tiers are then adapted for Côte d'Ivoire, Mali, Senegal and Kenya (high: $8, medium: $6, low: $2), and for Tanzania and Uganda (high: $8, medium: $3, low: $2), using GSMA data as the median value (GSMA, 2020), and then low and high values selected based on consumer price research for different mobile services. Revenue is converted over the 10-year assessment period to the present value (PV) in the initial year using a discount rate of 5% to represent the time value of money due to inflation, with this value informed by IMF consumer price projections (International Monetary Fund, 2021).

3.3. High-resolution spatial estimation of least-cost networks

The network design module estimates the least-cost design to connect communities without cellular coverage. Firstly, a baseline is established for existing infrastructure using a range of data sources. Long distance fiber links are extracted from the African Terrestrial Fiber map (Network Startup Resource Center, 2020), and fiber Points of Presence (POPs) are estimated based on large settlements exceeding 20,000 inhabitants located within 5 km of a fiber edge. Secondly, existing sites in each region are estimated to obtain the total existing site density using either geolocated site data, or disaggregated estimates of tower counts by country, as detailed in Section S1 of the Supplementary Materials.

A standard way to dimension a cellular network is using three cells per site, thus producing geometric hexagons (Holma and Toskala, 2012). Of the total existing site density in each area, the hypothetical MNO modeled has a site density relative to its market share. So, an MNO with 30% market share, is treated as having a site density which is approximately 30% of the total site density. Sites are allocated a technology, such as 2G, 3G or 4G, by intersecting the estimated site locations with the coverage map polygons from the global Mobile Coverage Explorer (Collins Bartholomew, 2019).

To ensure the analysis is logical, certain areas need to be excluded to avoid overestimation. Firstly, all statistical areas with a name identifier containing 'lake' are excluded, to prevent the model overbuilding infrastructure on large water bodies. Secondly, for the vast Saharan desert (covering over 9 million km^2), existing statistical boundary products often diverge in their zoning of these regions, with some statistical areas having diameters over 1 million kilometers. Therefore, for the northeastern part of Mali, where statistical boundaries differ considerably in size from other regions being assessed, nine statistical areas are excluded, constituting only 0.4% of the modeled population. If these areas are not excluded, terrestrial investment costs are overestimated. Other analyses exclude the hardest-to-reach 10% to 20% of the population, assuming satellite will be the only option to connect in these areas (International Telecommunication Union, 2020), so despite these exclusions this analysis still assesses universal broadband reaching 99.6% of the total population.

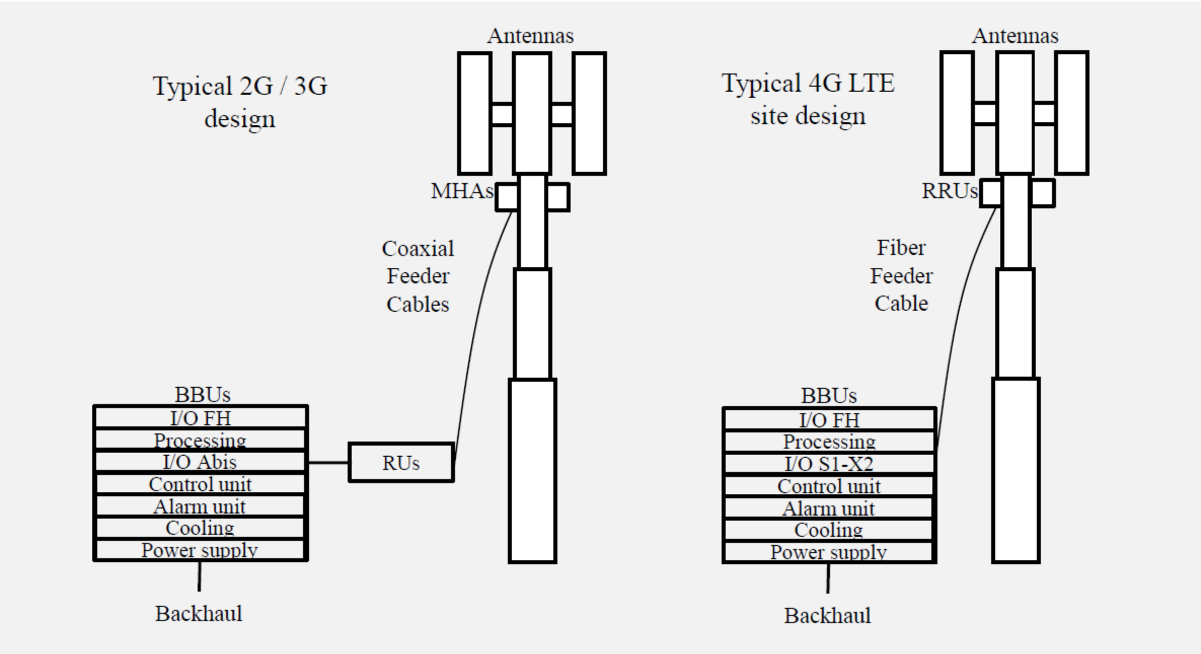
To estimate baseline capacity both current and future spectrum bands are used for the assessment period. Average downlink spectrum portfolios for a hypothetical MNO are identified for Côte d'Ivoire (3G: 15MHz@2100MHz and 4G: 10MHz@ 800MHz), Mali (3G: 10MHz@2100MHz and 4G: 10MHz@700MHz), Senegal (3G: 10MHz@1800MHz and 2100MHz, and 4G 10MHz@800MHz and 1800MHz), Kenya (3G: 20MHz@1800MHz and 4G: 10MHz@700MHz and 800MHz), Tanzania (3G: 10MHz@1800 MHz and 2100MHz and 4G: 10MHz@ 700MHz and 1800MHz) and Uganda (3G: 10MHz@1800 MHz and 2100MHz, and 4G: 10MHz@800MHz and 1800 MHz) using available country information (Frequency Check, 2021). To reiterate, these bands constitute an average MNO spectrum portfolio, therefore representing a fraction of the total nationally available spectrum portfolio for each country.

The backhaul for the sites in each region is estimated based on statistics reported by GSMA on the existing composition of technology types by global region (GSMA, 2019b). For Sub-Saharan Africa the current backhaul composition is 4% fixed fiber, 6% fixed copper, 84% wireless and the remaining 6% using satellite. A least-cost design is also used to connect areas via a backhaul link into the main fiber network. Using a minimum spanning tree, the cheapest network structure to connect all regional nodes and sites is estimated, which can either be linked using fiber or a wireless technology (as illustrated in Figure S4 of the Supplementary Materials).

Once the additional sites required and the distance of the backhaul links are known, costs can be developed using estimates from a literature survey (5G NORMA, 2016; Frias and Pérez, 2012; Johansson et al., 2004; Markendahl and Mäkitalo, 2010; Paolini and Fili, 2012; Smail and Weijia, 2017), combined with validation by local operators. Mean per site capex costs include $40k for all active equipment, $30k to build a full 30m tower and $30k for installation. Mean per site opex costs include operation and maintenance of $7.4k, power of $3k, along with site rental of $10k (urban), $5k (suburban) and $3k (rural). For the backhaul, mean fiber costs per meter are $25, $15 and $10 for urban, suburban and rural respectively. Mean wireless backhaul costs are based on $15k, $20k and $45k for each small (<10km), medium (<20km) and large (<40km) backhaul unit (of which two are required to form a wireless connection). Connections over 40km require multiple hops (Kusuma and Boch, 2021; Oughton et al., 2022a). Core and backhaul links use an annual opex of 10% of the initial capex required for all active equipment to cover network maintenance and operation (Vannieuwenborg et al., 2018). An administration cost of 10% of the RAN cost is added to cover all necessary operations activities (subscriber acquisition, marketing, R&D etc.), which is below high-income countries (Rendon Schneir et al., 2019), although labor costs are substantially lower in the countries assessed here. The cost calculations estimate the PV over the assessment period (2020-2030) using a discount rate of 5% to account for inflation (International Monetary Fund, 2021). A market-set Weighted Average Cost of Capital of 15% is used broadly reflecting the risk of capital lending for the countries included (WACC Expert, 2020). Three input cost scenarios are applied, with the baseline being the costs described here, derived from the literature. The low and high scenarios then represent a ±20% change in the cost inputs from the baseline.

The network architectures for each type of cell site are shown in Figure 4, with only minor differences between them compared to newer 5G Cloud-RANs being deployed in frontier economies. Each generation of cellular technology used here is based on a traditional distributed basestation architecture, with the differences being mainly technical, such as the use of Mast Head Amplifiers (MHAs) in 3G versus Remote Radio Units (RRUs) in 4G.

Figure 4 Cell site design for different technologies



3.4. Assessment method

In the assessment module, spectrum costs are added to the deployment cost for each ith region for coverage and capacity bands (<1GHz and >1GHz, respectively) as follows: $Spectrum_i = \sum f\ (Price_{MHz} \cdot BW_f \cdot Pop_i)$. Spectrum prices are taken from a spectrum auction database (TeleGeography, 2020), enabling broadly reflective historical costs to be estimated for Côte d'Ivoire, Mali and Uganda (coverage: $0.02/MHz/population and capacity: $0.01/MHz/population), and Senegal, Kenya, and Tanzania (coverage: $0.1/MHz/population and capacity: $0.08/MHz/population). This follows a standard approach in the literature (Oughton and Jha, 2021).

The taxation rate for each country is taken from a global corporation tax database, with the rate being 30% in each country, except Côte d'Ivoire which is 25% (Tax Foundation, 2020). The MNO is then allocated a 10% Net Operating Profit After Taxes Margin (NOPAT) as the return for taking the investment risk associated with the network deployment, which is consistent with data on mobile industry financial performance (Applied Value, 2016). If gross profits are extracted, infrastructure can only be viably deployed in urban and suburban areas, leaving large rural areas uncovered, which is not conducive for universal broadband. Hence, excess capital beyond the 10% profit margin is reallocated to the next most viable region via a process of user cross-subsidization (Curien, 1991; Glass and Tardiff, 2021). This is essentially a universal service obligation. After this reallocation process is completed, any areas which remain unviable will require state funded subsidization, but as state funds are limited, this is therefore a last resort.

Additionally, the private cost to the MNO in the ith region is estimated based on the sum of the network, admin and operations, spectrum, taxes and profit ($PrivateCost_i = Network_i + Administration_i + Spectrum_i + Taxes_i + Profit_i$). Finally, the net cost to government in the ith region is treated as the required state subsidy minus any revenues gained from spectrum fees and taxation ($GovernmentCost_i = Subsidy_i - (Spectrum_i + Tax_i)$). Once the private and government costs have both been obtained, it is possible to estimate the financial cost to society by finding the summation of the two variables ($FinancialCost_i = PrivateCost_i + GovernmentCost_i$). For the individual country assessments, the total market investment to deliver universal broadband is reported, by multiplying the cost per user by the number of users needing to be connected.

A summary of all model input parameters can be found in Table 2.

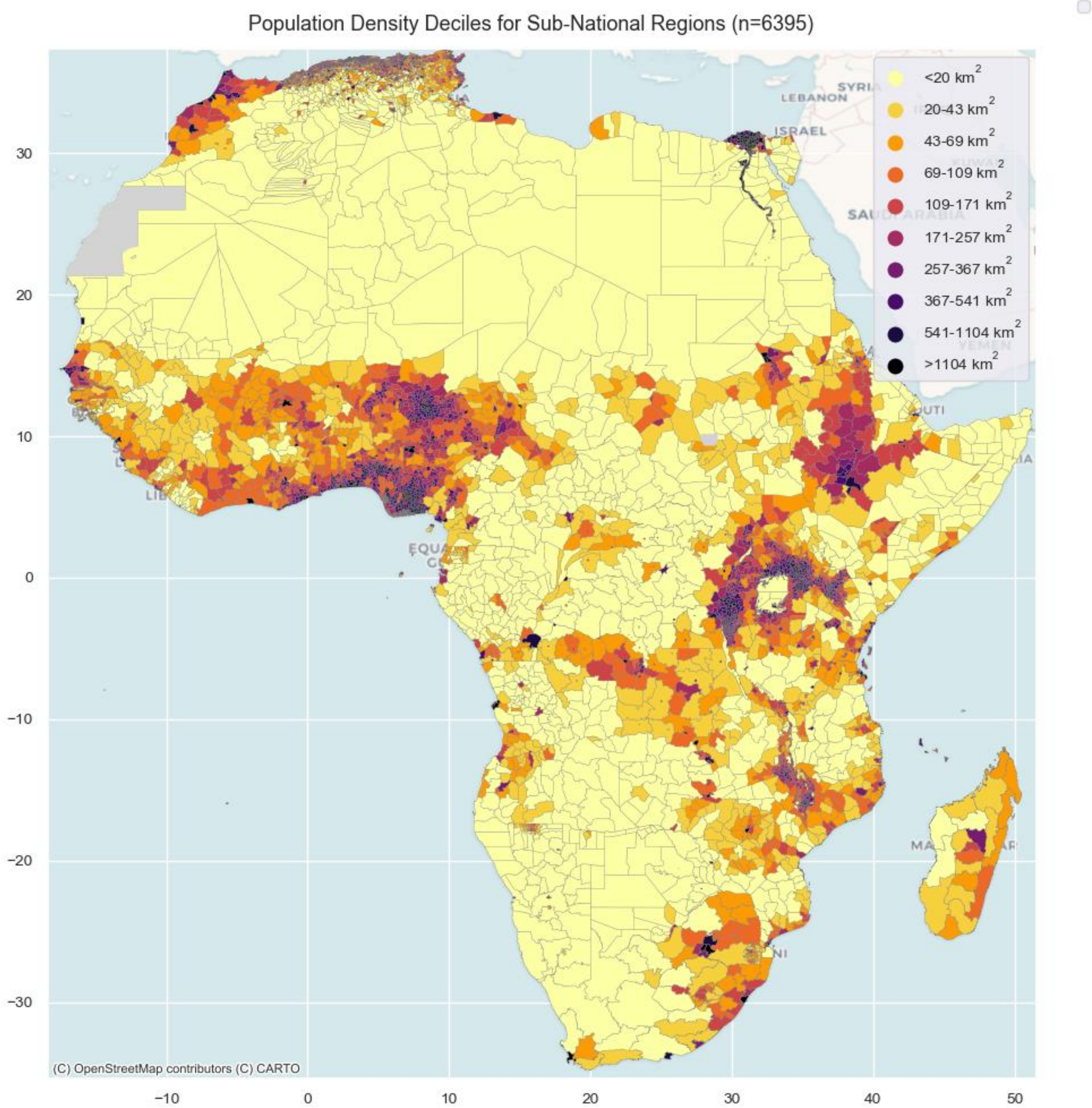
Table 2 Summary table of model inputs

Category	Parameter	Unit	Côte d'Ivoire	Mali	Senegal	Kenya	Tanzania	Uganda
Country and scenario information	**Country ID**	ISO3	CIV	MLI	SEN	KEN	TZA	UGA
	Regional level	GADM GID	2	2	2	3	2	2
	Regional nodes level	GADM GID	1	2	2	2	1	2
	Spectrum cost (<1 GHz)	USD/MHz/pop	0.04	0.04	0.04	0.1	0.1	0.1
	Spectrum cost (>1 GHz)	USD/MHz/pop	0.03	0.03	0.03	0.08	0.08	0.08
	Taxation (High)	%	40	40	40	40	40	40
	Taxation (Baseline)	%	25	30	30	30	30	30
	Taxation (Low)	%	10	10	10	10	10	10
	Cost Inputs (High)	%	+20	+20	+20	+20	+20	+20
	Cost Inputs (Baseline)	%	0	0	0	0	0	0
	Cost Inputs (Low)	%	-20	-20	-20	-20	-20	-20
Spectrum portfolio	**3G frequencies**	MHz	1800	1800	1800	1800	1800	1800
	3G bandwidth	MHz	2x10	2x10	2x10	2x10	2x10	2x10
	4G frequencies	MHz	800	700	800	700	700	800
	4G bandwidth	MHz	2x10	2x10	2x10	2x10	2x10	2x10
Cost model parameters	**WACC**	%	15	15	15	15	15	15
	Return Period	Years	10	10	10	10	10	10
	Discount rate	%	5	5	5	5	5	5
	Opex as a proportion of capex	%	10	10	10	10	10	10
	Profit margin	%	10	10	10	10	10	10
	Admin proportion of network	%	10	10	10	10	10	10

3.5. Continent-wide estimation method

Once the financial costs (private and public) per user have been estimated for each of the six detailed country assessments, the mean cost per user is extracted for each population density decile. To scale the results across the African continent, the mean cost per user is multiplied by the population in each local region to gain an estimate of the required total investment, representing the cost for all network operators to achieve universal broadband. Such a method relies on the fact that population density is the main driver of the cost of infrastructure delivery (Oughton and Russell, 2020), because large up-front fixed capital costs are required to build infrastructure assets before a single user can be served (Hall et al., 2016b). Figure 5 illustrates the population density for all local regions extracted from the Database of Global Administrative Areas (GADM, 2019) using the WorldPop settlement layer (Tatem, 2017; WorldPop, 2019). The importance of strategically mapping spatial rural broadband information is well recognized (Hambly and Rajabiun, 2021). Further information on the decile segments can be found in Table S1 of the Supplementary Materials.

Figure 5 Distribution of population density deciles across the African continent



4. Results

The present value of the financial cost is presented in Figure 6 for each of the six countries analyzed under the low, baseline and high adoption scenarios, as well as the two different capacity per user targets (10 and 30 GB/month). The results show that 3G is more costly than 4G to deploy, as the lower spectral efficiency means more sites are needed to provide universal broadband for either capacity target. On average, 4G is between 20%-47% less expensive than 3G when using either a wireless or fiber backhaul to deliver 30 GB/month (or 7%-57% for 10 GB/month), suggesting there is motive for ‘leapfrogging’ straight to a more recent cellular technology. Add to this the ability to have a core network based on the Internet Protocol (IP) (an Evolved Packet Core) and 4G becomes an even more appealing technology choice. Additionally, a wireless backhaul is frequently more than half the cost of using fiber for delivering universal broadband, with savings of 38%-70% for 10 GB/month and 32%-63% for 30 GB/month. The visualization also demonstrates that the lower capacity per user target of 10 GB/month is substantially cheaper than the 30 GB/month target.

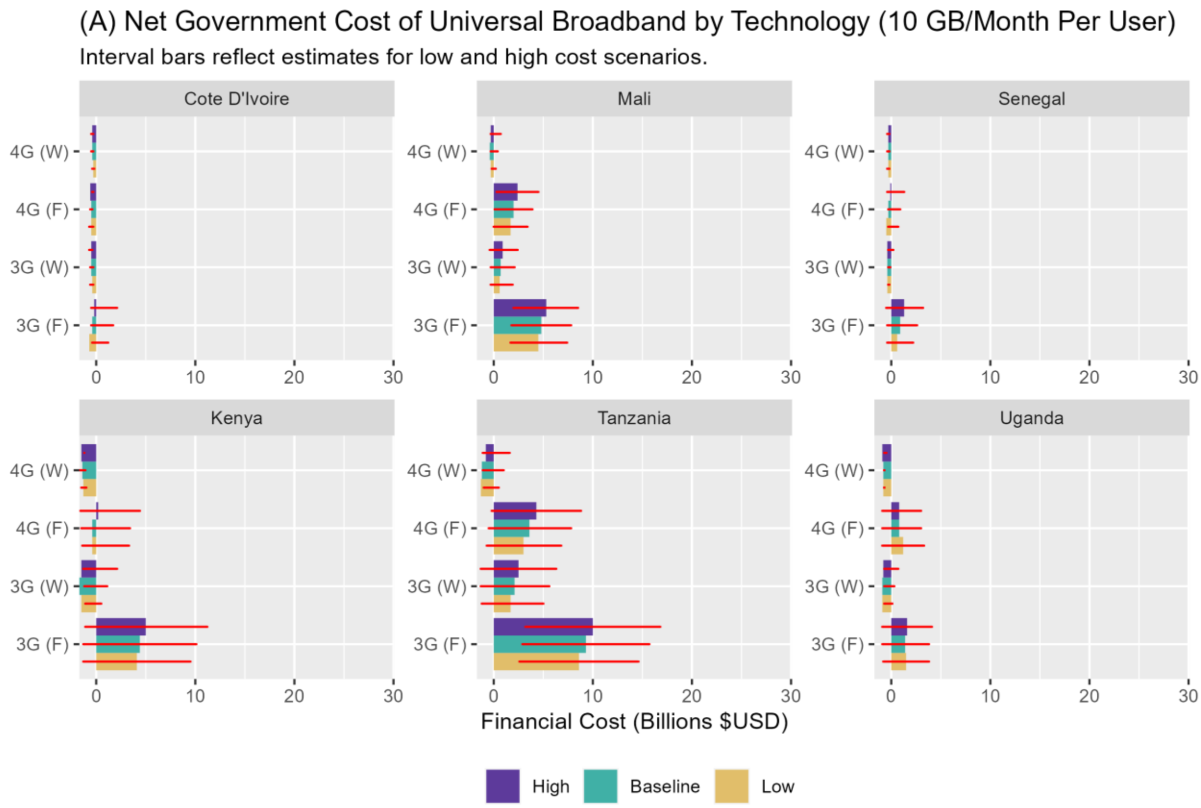
Figure 6 Financial cost of technology strategies

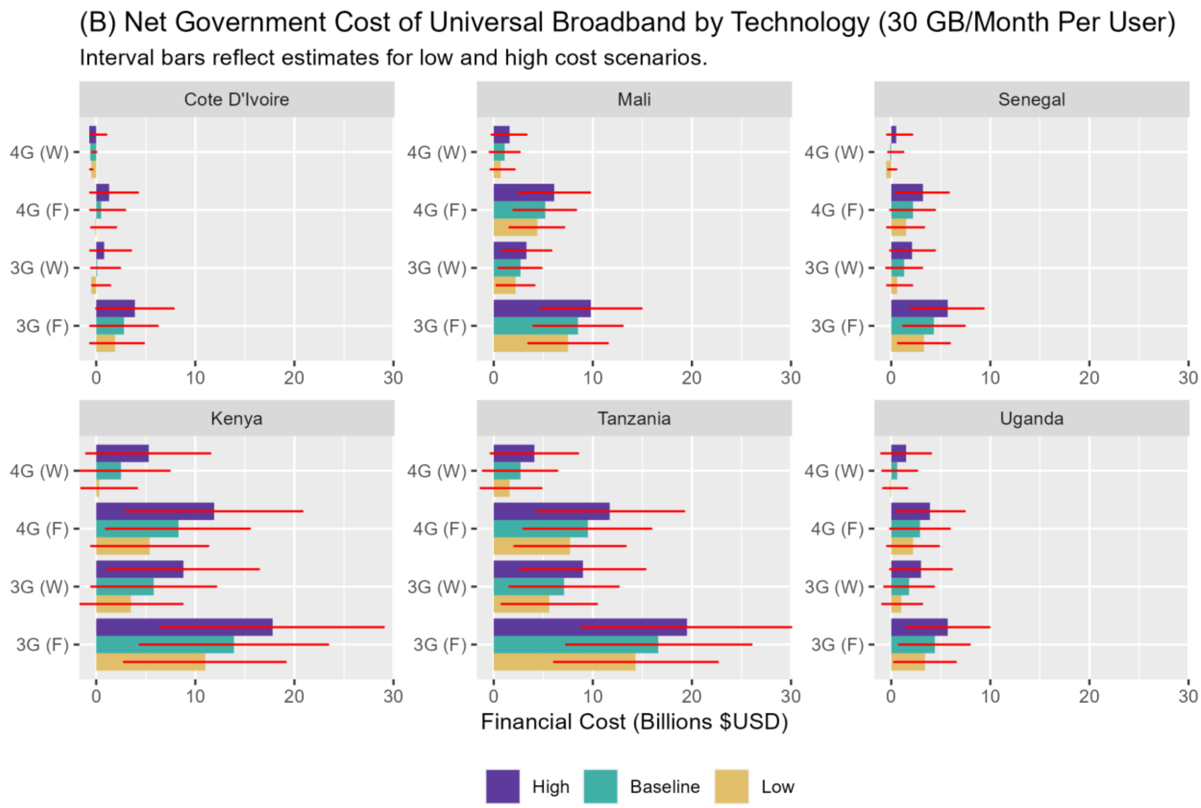
The financial cost displayed in Figure 6 has the quantity of state subsidy required to achieve universal broadband embodied within it, therefore in Figure 7 this government cost is explicitly reported.

Positive values represent a cost to government, whereas negative values represent a net revenue to government (from spectrum licensing fees and taxation). Most of the scenarios and strategies require large state subsidy support for a target of 30 GB/month, even for the cheapest strategy of using 4G with a wireless backhaul. For example, across the scenarios and strategies, only Côte d'Ivoire and Senegal could viably achieve 30 GB/month universal broadband without state support (but only for certain low and baseline scenarios). In contrast, a target of 10 GB/month shows much more minimal public subsidy requirements, and in most countries, a net revenue stream for governments.

Where technologies cannot be viably delivered nationally, then in the model specified, every $1 of revenue taken by government, equates to $1 of expenditure in the form of an infrastructure subsidy to unviable areas. Indeed, Figure 7 demonstrates that by choosing a more expensive technology, such as 3G, the magnitude of the government cost in the form of an infrastructure subsidy increases considerably.

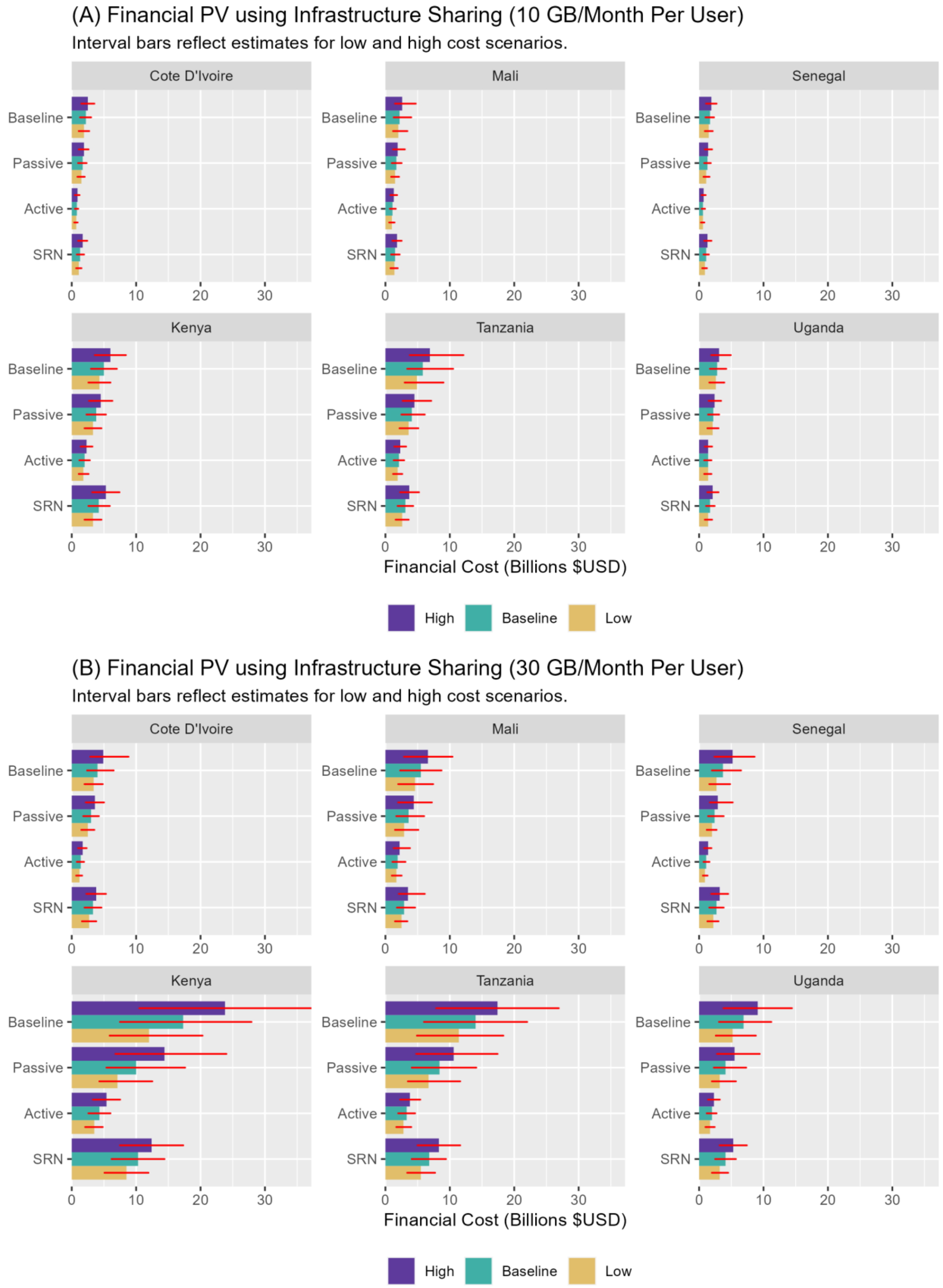
Figure 7 Government cost of technology strategies (negative values indicate a revenue surplus)





Given the large government costs involved particularly with the 30 GB/month target, Figure 8 illustrates the financial cost savings possible from infrastructure sharing strategies. Passive sharing strategies exhibit substantial savings between 18%-34% for 10 GB/month and 26%-44% for 30 GB/month against the baseline. Moreover, active sharing strategies via a Multi Operator Radio Access Network (MORAN) result in savings between 48%-67% for 10 GB/month and 64%-78% for 30 GB/month but comes with the caveat that such an approach would sacrifice competitive infrastructure effects. Finally, a shared rural network provides impressive efficiencies given the approach preserves infrastructure competition in urban and suburban areas, with a saving against the baseline of 11%-47% for 10 GB/month and 18%-52% for 30 GB/month per user.

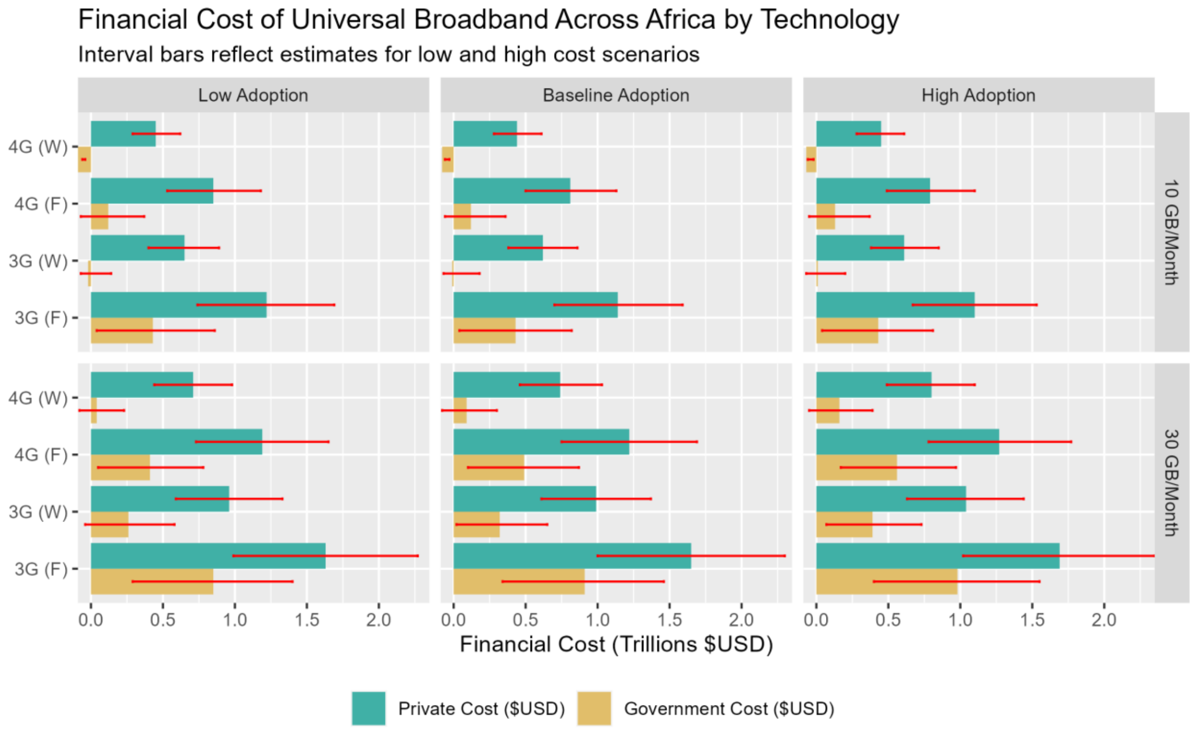
Figure 8 Financial cost of infrastructure sharing



As per Section 3.5, once the mean financial cost per user by population decile has been obtained, the cost for connecting all users across Africa can be developed. The results are reported in Figure 9. The estimates have been broken down by both the private and government cost composition.

For the 30 GB/month per user target, the cheapest option is using 4G with a wireless backhaul, with a financial cost for 2020-2030 ranging from $0.7 trillion to $1 trillion between the low and high adoption scenarios to achieve universal broadband. When compared to this option, deploying 3G with a wireless backhaul is estimated to be between 33%-39% more expensive across the scenarios for 30 GB/month.

Figure 9 Financial cost universal broadband across Africa by technology strategy



For a 10 GB/month per user target, the costs are substantially lower. Approximately $0.4 trillion is required to deliver universal broadband across Africa over 2020-2030 using 4G with a wireless backhaul. This equates to a cost saving of approximately 40% when targeting a per user consumption rate of 10 GB/month, compared to 30 GB/month. Moreover, this is also roughly 38%-41% cheaper than using 3G with the same backhaul technology. Both wireless options can be achieved using just private investment, with government gaining a small surplus (visible by the negative costs in Figure 9) thanks to revenues from spectrum licensing and taxation.

The spatial distribution of the financial cost per user is illustrated in Figure 10 and Figure 11 for the 30 GB/month and 10 GB/month targets, respectively. The financial cost per user in the highest population density deciles ranges from $300-$900 over 2020-2030 for 30 GB/month which is reasonably plausible (~$2.5-$7.5 per month), but this cost increases considerably to over $2,000 in many areas which will be unviable (>$16 per month) based on the low incomes of many potential users. Cost reducing options will be essential in the many areas shaded in the darkest colors, representing the hardest-to-reach deciles. Importantly, when contrasted with a more modest minimum target of 10 GB/month, as per Figure 11, we can see the cost in all areas sits within the more viable range of $300-$900 per user (so broadly $2.5-$7.5 per month). Section S3 (Figures S5-S10) of the Supplementary Materials provides detailed visualizations which map these costs in greater detail, including the government investment cost relative to the GDP of each country.

Figure 10 The universal broadband (30 GB/Month) per user financial cost across Africa

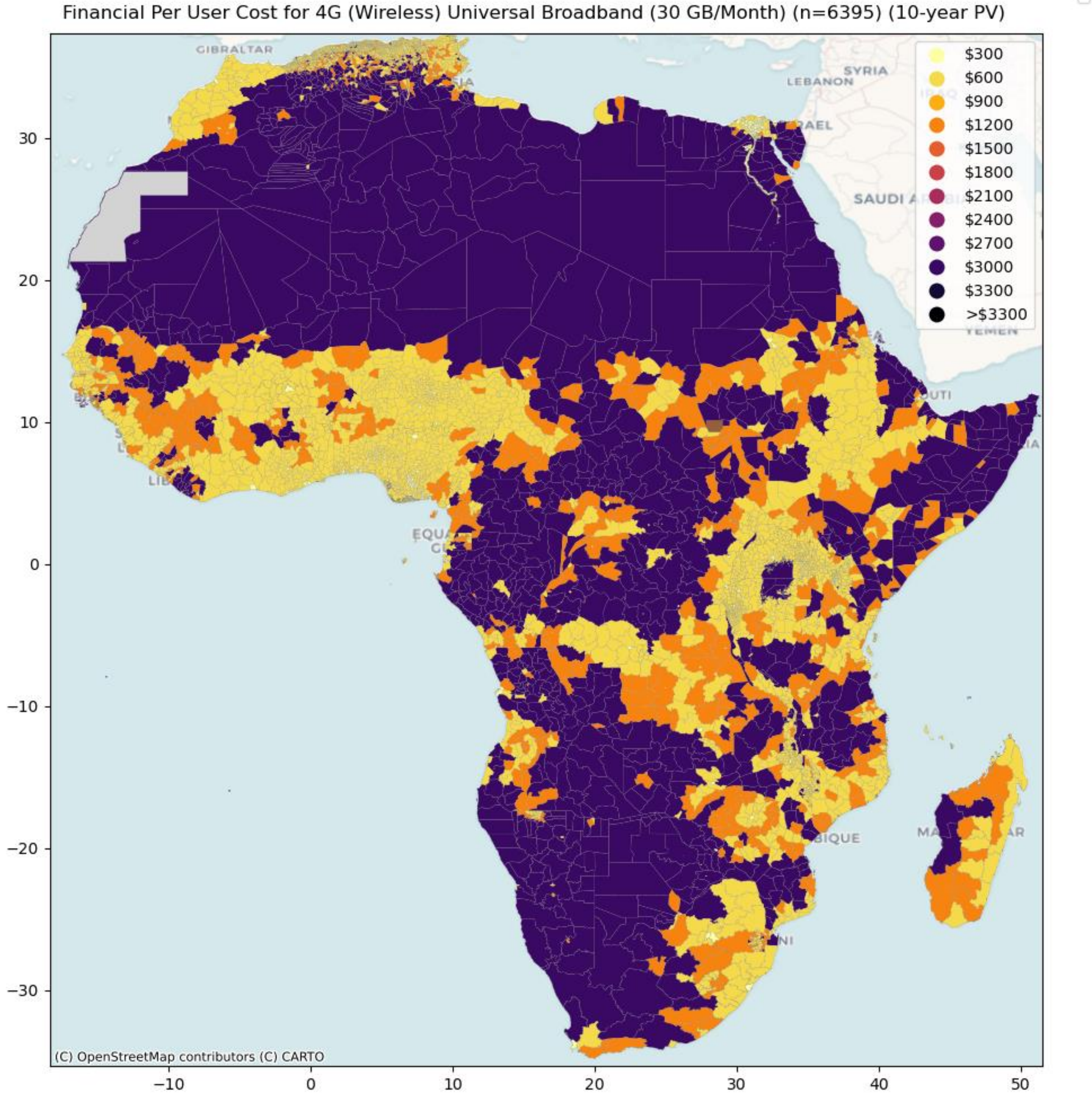
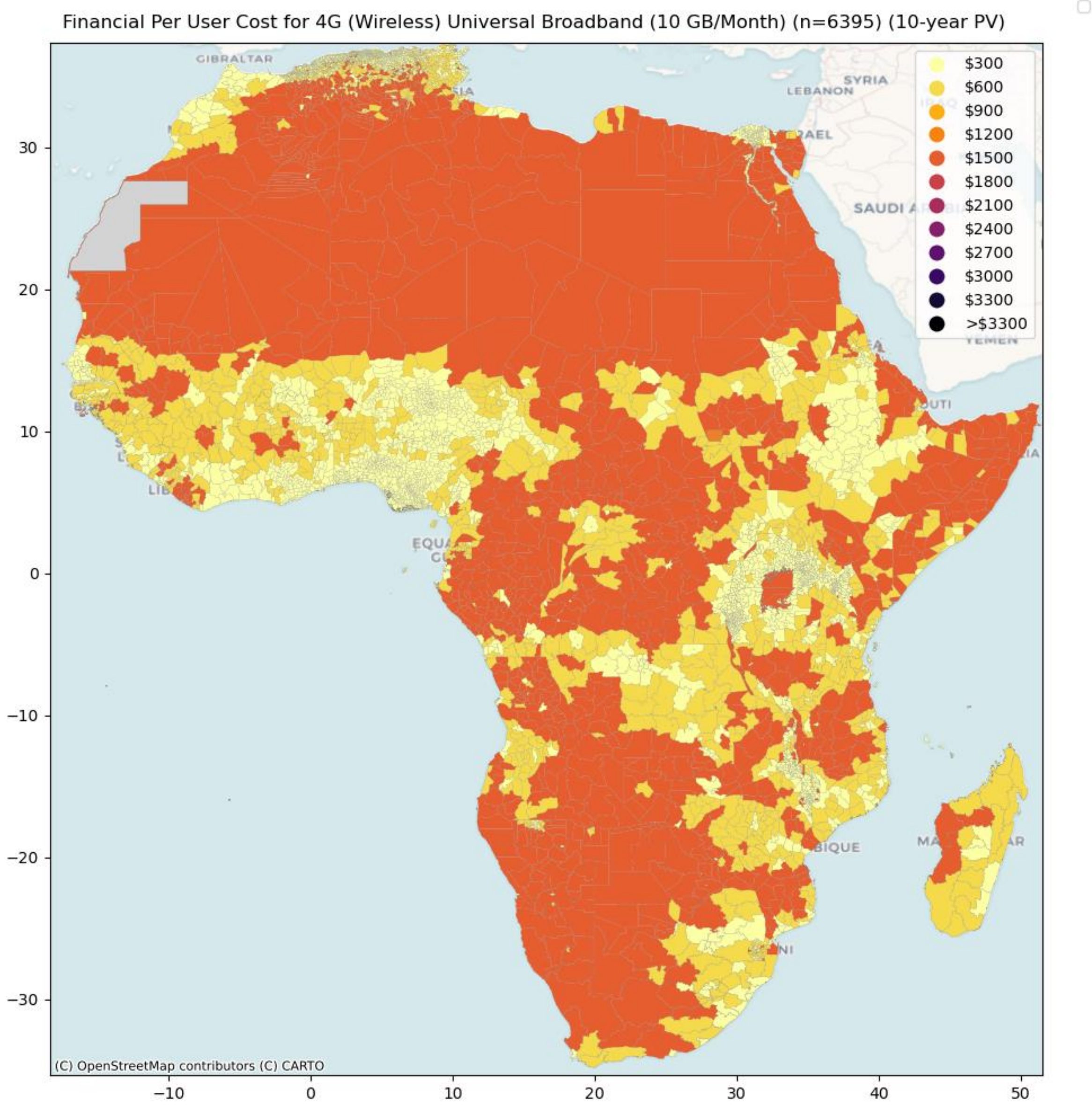


Figure 11 The universal broadband (10 GB/Month) per user financial cost across Africa



5. Results evaluation

How do the estimated results reported in Section 4 compare with other assessments? An evaluation will now be undertaken based on the main comparative study which is the United Nations Broadband Commission's assessment of universal broadband for Africa (Broadband Commission for Sustainable Development, 2019). The primary motivation for this evaluation is that (i) the appraisal is the only recent example of a continental assessment and (ii) it is the analytical foundation for the UN Broadband Commission's policy over the next decade (and therefore deserving of critical review).

Table 3 compares the key modeling differences between the two assessments, based on the methods and assumptions utilized.

Table 3 Comparison of key modeling differences

Method component	UN Broadband Commission	This Assessment
Broadband definition	~10 Mbps average speed	Either 30 GB/Month or 10 GB/Month
Quality of Service (QoS)	Not modeled	50% reliability in the busiest hour of the day
Users	Focuses on only unconnected users (excluding underserved users)	Includes both unconnected and underserved users
Technologies	Mainly 4G and satellite (but also fixed fiber)	Only 4G and fixed fiber (does not include satellite)
Demand approach	Penetration up to 90%	Forecasts of unique subscribers between 2020-2030
Universal broadband assumptions	Assumes 10-20% of the hardest-to-reach population use satellite	Models the full cost for terrestrial infrastructure strategies
Cost model components	Covers (i) infrastructure (capex and opex), (ii) policy and regulation costs and (iii) funding for ICT skills and content	Covers (i) infrastructure (capex and opex), (ii) network operator administration (opex), (iii) spectrum (capex and opex), (iv) taxation (opex) and (v) a profit margin (opex)
Societal costing method	Focuses on required gross investment	Calculates net private and government investment, converting these estimates to the societal financial cost
Government costing method	Focuses on required gross investment	Calculates the government subsidy required after user cross-subsidization

Generally, the UN assessment produces much smaller investment estimates than those presented in this paper. For example, the required investment to provide universal broadband across Africa is estimated to be approximately $100 billion, with countries needing to add approximately 1 billion users to 4G. This figure can be broken down based on ~$29.5 billion being spent on capex, ~$52 billion being spent on opex, ~$18 billion allocated to ICT skills and content, and the final ~$2.4 billion going to policy and regulation costs.

Based on the content of Table 3, the larger estimates in this analysis are driven by multiple methodological differences. Firstly, the focus on trying to integrate Quality of Service aspects for the 30 GB/month target drive up the quantity of required infrastructure and thus the required cost. In contrast, the UN study makes no guarantees for the speed target assessed, meaning users could suffer reliability issues. Secondly, by including both unconnected and underserved users, this analysis aims to ensure everyone has access to exchange the data targets set. In comparison, the UN approach only includes unconnected users, not the many millions of underserved users. Finally, the UN analysis uses a very strong assumption that the final 10%-20% of hardest-to-reach users will be served by satellite. However, this is without any engineering-economic assessment as to whether the stated target could be supported by existing or future networks. Existing analysis suggests LEO satellite networks provide impressive capacity and coverage, but would be unlikely to support such a larger number of users affordably (del Portillo et al., 2021; Osoro and Oughton, 2021; Pachler et al., 2021).

To conclude this evaluation, the UN method caveats the analysis by stating that the results should be considered as 'high-level and directional in nature' (p19) (International Telecommunication Union, 2020), and that more detailed modeling needs to be utilized at the country-level to provide a much more nuanced understanding of the investment requirements of each nation. This analysis has provided such detailed modeling, therefore making an important contribution to theory (in terms of the method framework) and application (insight into the costs of universal broadband using a more spatially granular approach).

6. Discussion and conclusions

Having reported the results, discussion will now be undertaken on both the research questions and the limitations of the assessment. The first research question stated in the introductory section was as follows:

Which technologies and infrastructure sharing policies should governments encourage to enable universal broadband?

Of the four different technology options tested, the cheapest deployment option across all scenarios and strategies was the combination of 4G with a wireless backhaul. This provides substantial evidence for those countries currently aiming to cycle through the cellular generations sequentially, to instead 'leapfrog' to providing 4G in underserved areas. Most of the investment saving comes from operating fewer sites, thanks to 4G being a more spectrally efficient technology deployed in frequencies with better propagation characteristics. However, there are also numerous benefits from having a more flexible IP-enabled core network making the 4G case even more convincing. The analysis demonstrates that the technology strategy has a very large impact on the viability of universal service broadband, and that using 4G with a wireless backhaul is the most cost-efficient way to push coverage out to rural and remote areas with low ARPU. This is particularly true when considering the different capacity targets, given that this technology option performs well when focusing on universal broadband of 10 GB/month per user.

Reflecting on the hypothetical modeling approach presented here, governments need to be aware that by deploying a higher capacity target or a more superior technology (e.g., 4G with fiber), there is ultimately less capital available to redeploy to unviable areas via user cross-subsidy, increasing the required state subsidy. Moreover, least-cost strategies (e.g., wireless-based 4G) can also be considered as having less risk overall, because higher cost strategies (e.g., fiber-based 3G) may be subject to greater cost overruns or miscalculations.

Infrastructure sharing has a very large impact on the cost of delivery, especially in helping to serve hard-to-reach areas. The caveat to these results is that governments must balance the desire to push out service to unviable areas (by reducing supply-side costs), against the benefits of competitive infrastructure markets. From decades of economic research, dynamic competition has demonstrated positive outcomes for consumers and the wider macroeconomy. However, issues arise in areas of market failure where the costs of supply exceed the potential revenues obtained from the available demand, therefore giving rise to one economic form of the 'digital divide'.

A major concern with the strategies tested is that infrastructure consolidation could decrease the level of market competition, which could be an unwise path to take. Active infrastructure sharing is a prime candidate despite delivering impressive savings (48%-67% for 10 GB/month and 64%-78% for 30 GB/month). While passive sharing strategies could also prove promising, providing average savings of 18%-34% for 10 GB/month and of 26%-44% for 30 GB/month, they are also nationally homogeneous in their approach, with no differentiation between sharing in viable and unviable areas. Therefore, the most promising option the analysis yields is a shared rural network because this approach is capable of balancing competitive markets in viable areas with enhanced sharing in less viable rural areas. Indeed, up to 52% of the cost saving could be achieved by only sharing infrastructure in rural areas, allowing urban and suburban areas to enjoy the benefits of dynamic competition between MNOs. Governments should therefore undertake their own detailed assessments of infrastructure sharing areas deemed to be too unviable to cover with existing terrestrial cellular business models.

Having discussed the first question, the second will now be discussed:

What magnitude of investment is required for universal broadband across the African continent, to achieve SDG Target 9c?

The very purpose of the individual country assessments was to be able to generalize the results obtained to the whole continent of Africa, using the mean cost for each population decile. Therefore, in answering this final research question, the analysis has made it possible to evaluate the cost performance of different technology options in providing universal broadband. To provide a per user capacity of 30 GB/month, the cheapest option is using 4G with a wireless backhaul. Indeed, the PV of the total financial cost for this technology ranges from $0.7 trillion to $1 trillion between the low and high adoption scenarios over 2020-2030 (equating to 33%-39% cheaper than 3G with a wireless backhaul). The financial cost drops considerably when considering a 10 GB/month per user target, with approximately $0.4 trillion required across the low and high adoption scenarios to deliver universal broadband across Africa using the same technology (4G with a wireless backhaul). Such an approach equated to a saving of roughly 38%-41% compared to using 3G with a wireless backhaul. A key caveat to all the supply-side cost estimates in this analysis is that the user device cost has been excluded.

6.1. Limitations

There are several limitations of this analysis which are worth discussing and identifying as areas of future research. Firstly, data limitations are a key issue, even for the six detailed country assessments. For example, a commitment was made to use the GSMA adoption data for unique mobile subscribers because the data set covers most countries globally, but there can be differences in these estimates compared to those released by the telecommunication regulators in various countries. This highlights the fact that it is challenging to undertake both detailed country modeling, while also aiming to provide breadth of analysis across an entire continent. Ultimately this leads to a trade-off in local data quality, to provide systematic insight at the continental scale. Further research should explore the implications of different distributional assumptions in the statistical generalization method applied here.

Secondly, the assessment was based on scenario analysis, and included forecasts for future demand based on a variety of different potential futures. Hopefully by using variation in these forecasts, the model was able to capture uncertainty around this key set of parameters, but it is also important to recognize these comparative scenarios are not necessarily predictions. Moreover, the exogenous treatment of cell phone adoption is a simplification and overlooks the fact that adoption may be dependent on the quantity of infrastructure deployed. In general, future research needs to focus more on demand-side aspects, particularly the impact of device affordability.

Thirdly, the analysis in this paper does not consider other non-cellular technology options. For example, satellite broadband via LEO Constellations could provide broadband services in very remote low population density areas, relative to the terrestrial cellular approach assessed here. Indeed, this is a cornerstone of the UN Broadband Commission's analysis (although no explicit modeling of this sector is undertaken). Therefore, future research should account for multi-technology strategies to provide comparative analytics on the niche that each combination of options is best suited to, explicitly including the modeling of satellite networks (particularly, LEO constellations). Moreover, it would also be a useful exercise for future research to break down cost estimates into similar categories as the UN Broadband Commission's assessment, enabling better comparison of the investment costs for connecting unconnected and underserved users.

Finally, in this analysis the results were generalized from detailed country assessment to the whole continent of Africa using population density. While this metric is the key factor which affects the cost of deployment, using a single metric is also a limitation, therefore future work should expand this univariate approach to one that adopts a multivariate method, potentially introducing other factors such as topography.

6.2. Conclusions

This paper has contributed new data analytical methods which could in the future improve the design of national and international policies aimed at universal broadband. Indeed, the engineering-economic simulation methods put forward in this paper are likely to become even more important in the future as the cost efficiency of 5G and 6G technologies is increasingly highlighted (Oughton and Lehr, 2022; Yaacoub and Alouini, 2020; Zhang et al., 2020).

The results suggest that 'leapfrogging' to 4G is more cost efficient than 3G for providing universal broadband, with savings between 7%-57% for 10 GB/month and 20%-47% for 30 GB/month. Moreover, the cost for connecting all unconnected and underserved users across Africa can be reduced by approximately 40% by targeting a per user consumption rate of 10 GB/month, compared to 30 GB/month.

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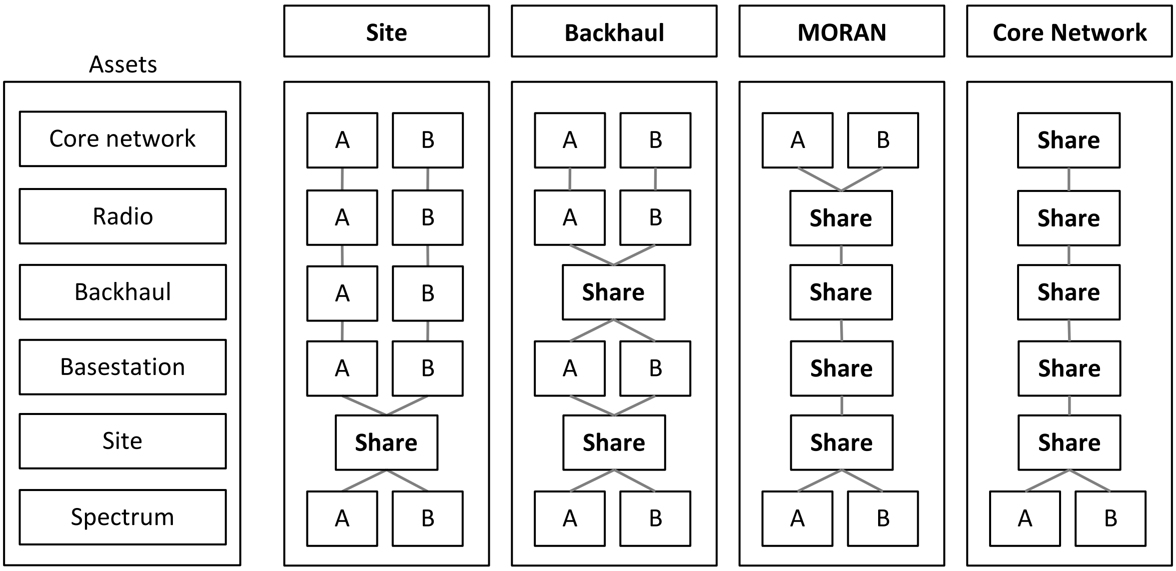
Supplementary Materials

Figure S1 Infrastructure sharing strategies (GSMA, 2019c)



Section S1 Site estimation method

For those countries where detailed site information is not available, a disaggregation method is adopted. Equation (S1) details how the sites ($Sites_i$) in the ith area are rank estimated given the local population (Pop_i), the total number of sites nationally ($Total\_Sites$), the total population nationally ($Total\_Pop$), and the percentage of the population covered nationally with cell phone access ($Total\_Coverage$).

$$Sites_i = Pop_i \cdot \frac{Total\_Sites}{(Total\_Pop \cdot (Total\_Coverage/100))} \quad \text{(S1)}$$

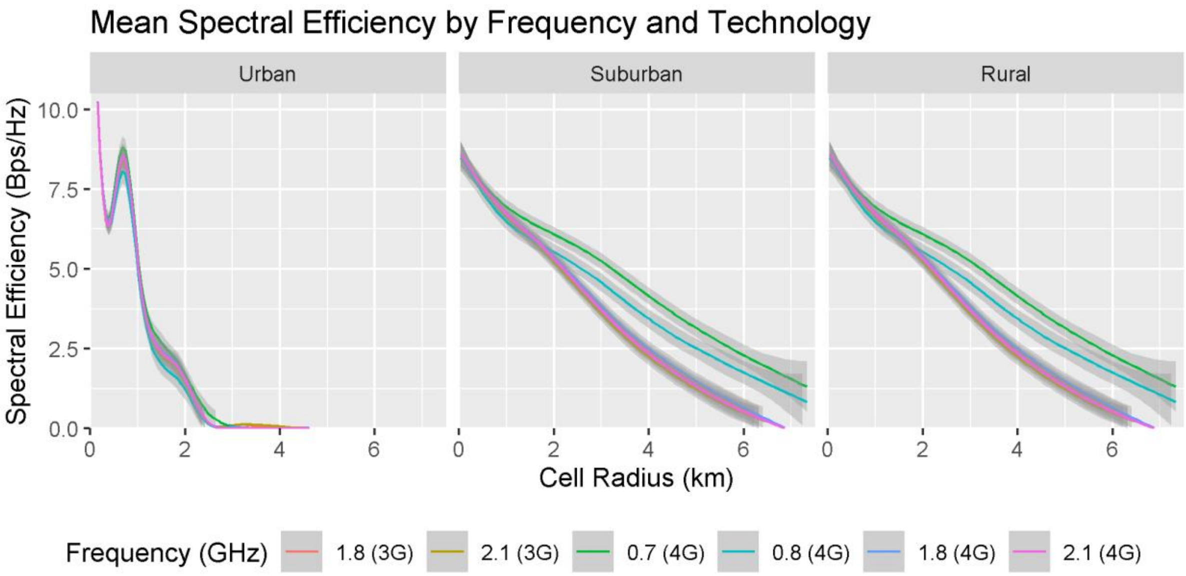
To allocate these sites, all regions are sorted based on population density, with the highest population density areas at the top of the list, and lowest population density areas at the bottom. The sites are allocated to the most densely populated regions first using equation (S1), meaning eventually all towers are allocated and those areas at the bottom of the ranked list receive no existing assets. These remaining areas are therefore the places of existing market failure which need serving.

Actual site data sets are provided by the Governments of Senegal and Kenya. In Senegal, the geospatial data are only for Sonatel (Orange), representing 15,302 cells and 1,711 unique sites. The sites per region are calculated and using Sonatel's market share (~54%) (BuddeComm, 2020) used to obtain a total market estimate, resulting in 3,170 sites nationally, which is very close to other estimates of 3,151 (TowerXchange, 2018). The benefit of this approach is that the estimates are built into the geospatial structure of the network data provided, reducing uncertainty. In Kenya, after removing incomplete entries, a total of 84,342 spatially located cells were obtained, leading to 13,745 unique cell sites. Tower count estimates are used of 4,412 in Côte d'Ivoire, 1900 in Mali and 3,554 in Uganda, as well as an estimate of 8,287 cells in Tanzania (TowerXchange, 2018).

Section S2 Network capacity estimation method

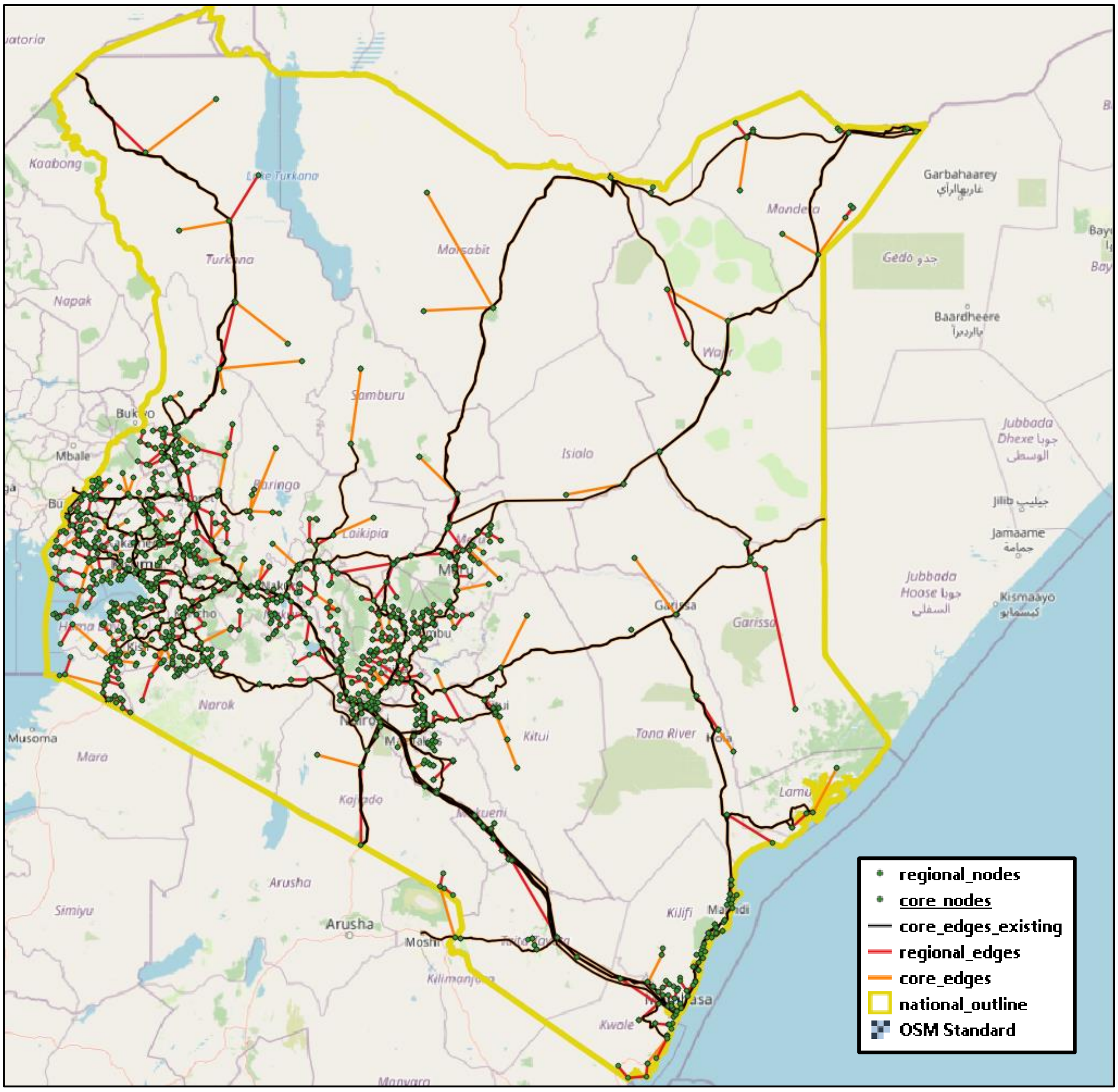
From the literature, a method is used to estimate downlink network capacity based on spectral efficiency, the site density and spectrum bandwidth. The open-source python simulator can estimate cellular capacity for 3G, 4G and 5G using a 3GPP stochastic propagation model (ETSI TR 138 901) to simulate the path loss attributable to irregular terrain, buildings, and other environmental cluster for different radio frequencies. A transmitter height of 30m is used along with a power of 40 dBm, with all detailed simulation parameters reported in the original publications (Oughton et al., 2019). Both 3G HSPA+ and 4G LTE use 2x2 MIMO up to 64 QAM. Spectral efficiency values for different technologies are mapped to the Signal-to-Interference-plus-Noise (SINR) ratio using either 3G or 4G modulation and coding lookup tables, using a standard cellular dimensioning approach (Holma and Toskala, 2011). Each macro site has three sectors, following a standard cellular network dimensioning method, hence leading to hexagonal cell areas. To obtain the least-cost RAN design for a specific traffic demand, the site density is minimized. After subtracting existing sites from the minimum number of total sites, the estimated quantity of required greenfield or upgraded brownfield sites can be estimated. A set of capacity-demand lookup tables are then generated for the model which enables site density to be mapped to a mean spectral efficiency, for each generation, frequency band and environment (urban or rural), as illustrated in Figure S2.

Figure S2 Stochastic simulation results by frequency and technology



In Figure S3 an example of a least-cost network design for Kenya is presented. The existing fiber network is in black, while new core fiber links are in orange, and red links are either fiber or multi-hop wireless connections depending on the strategy.

Figure S3 Example of a least-cost network design for Kenya



Section S3 Supplementary results

Figure S4 Per user private cost for universal broadband across the African continent (30 GB/Month)

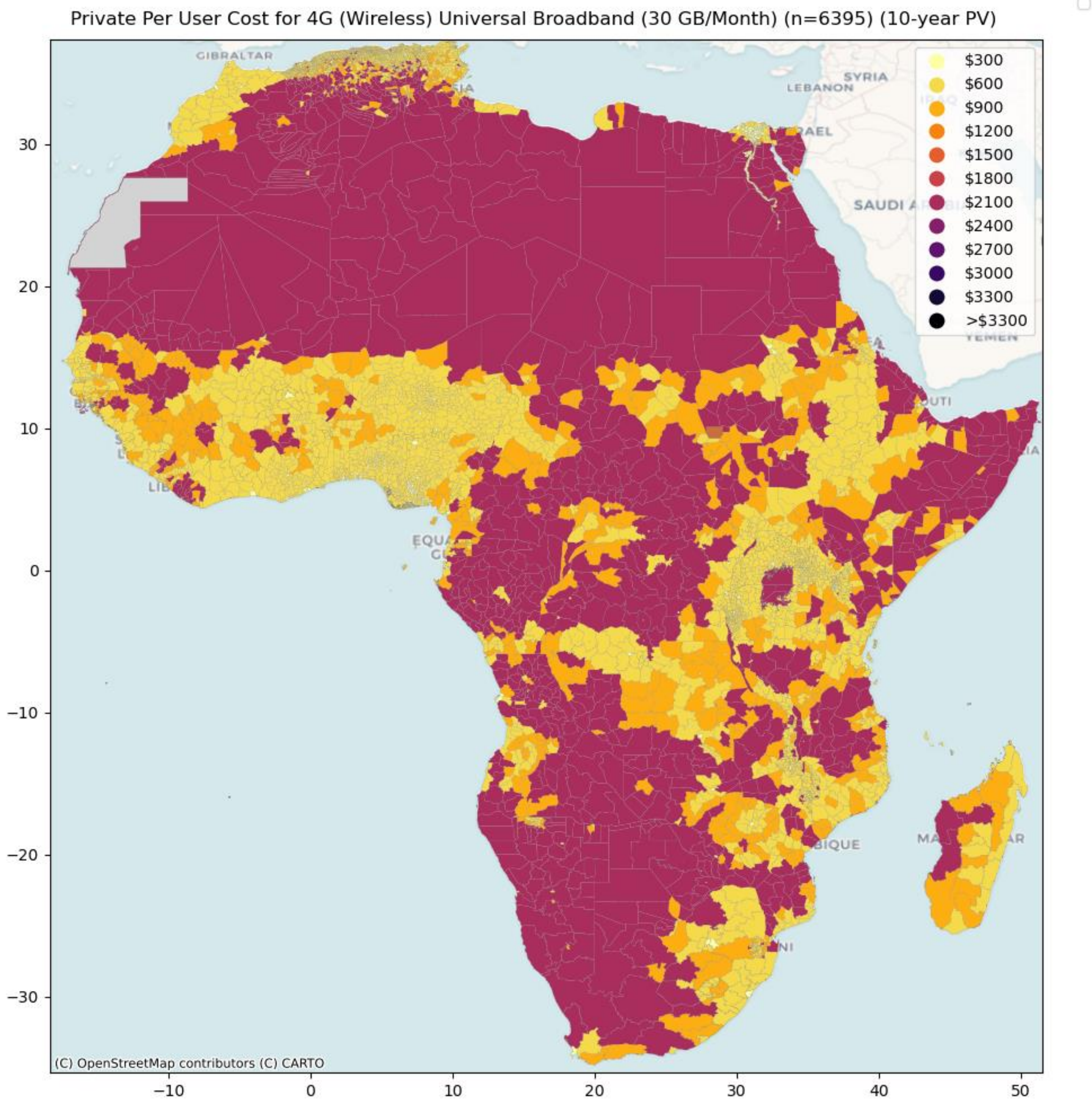


Figure S5 Per user government cost for universal broadband across the African continent (30 GB/Month)

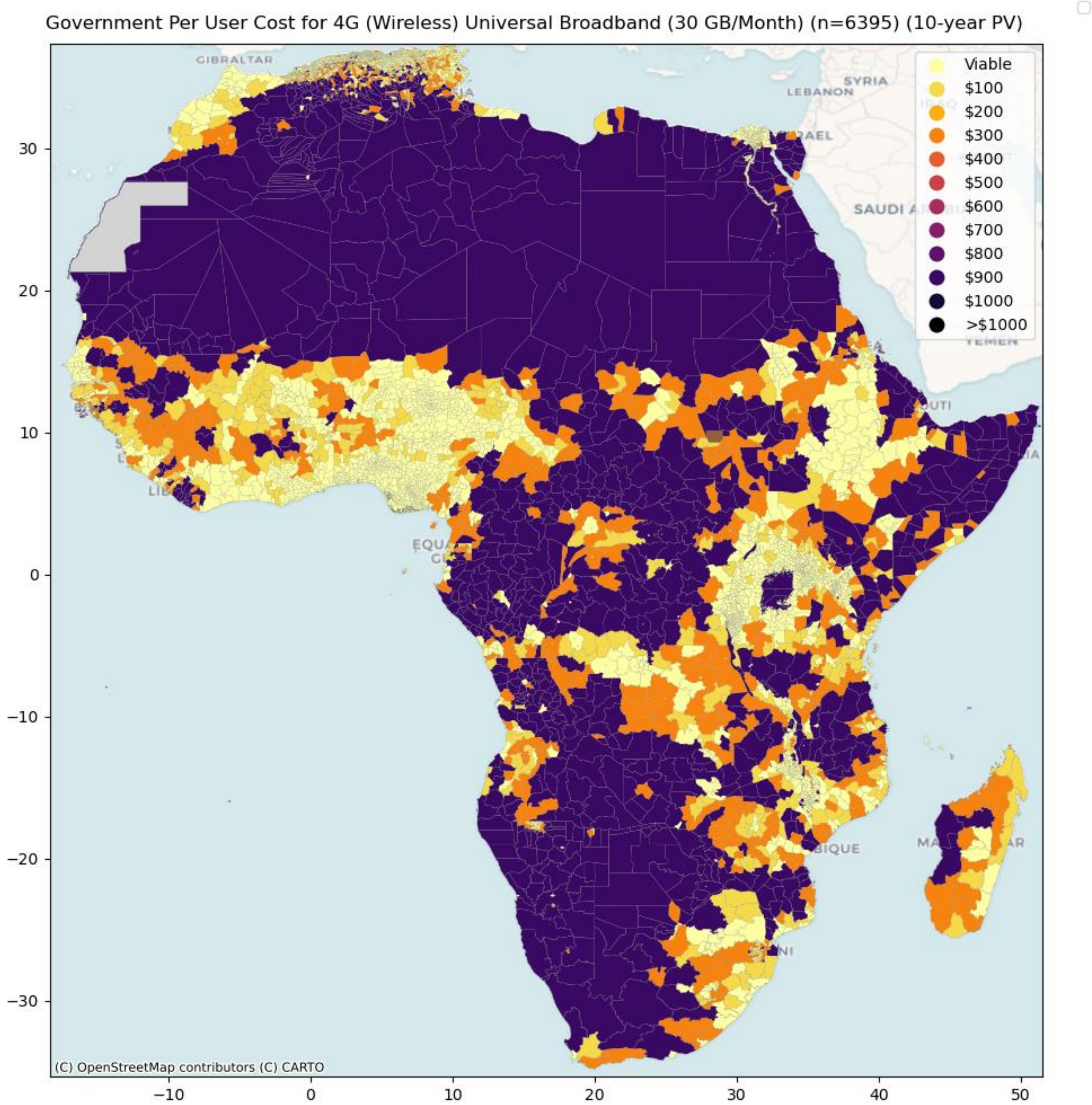


Figure S6 Government cost as a percentage of GDP for universal broadband (30 GB/Month)

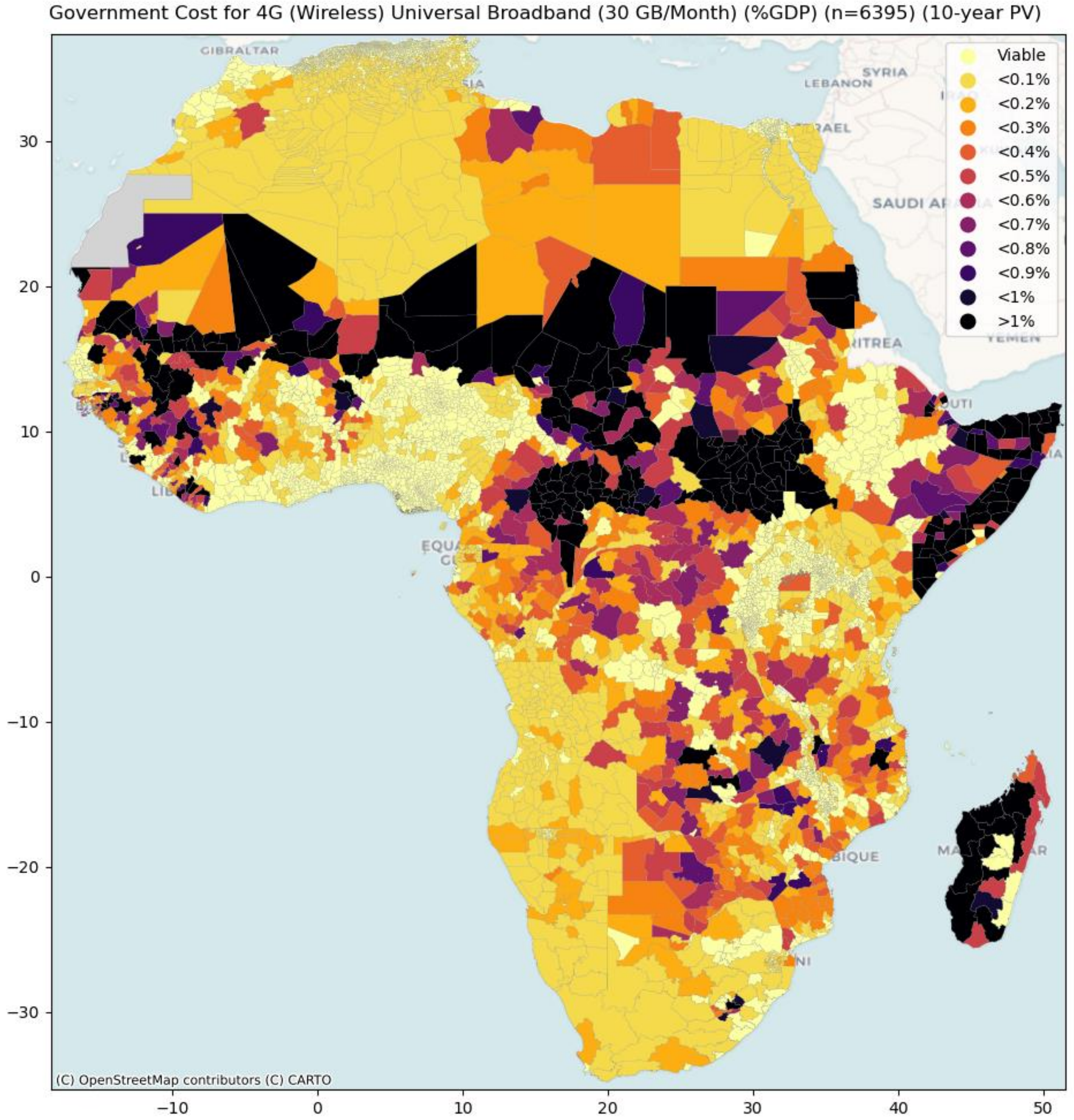


Figure S7 Per user private cost for universal broadband across the African continent (10 GB/Month)

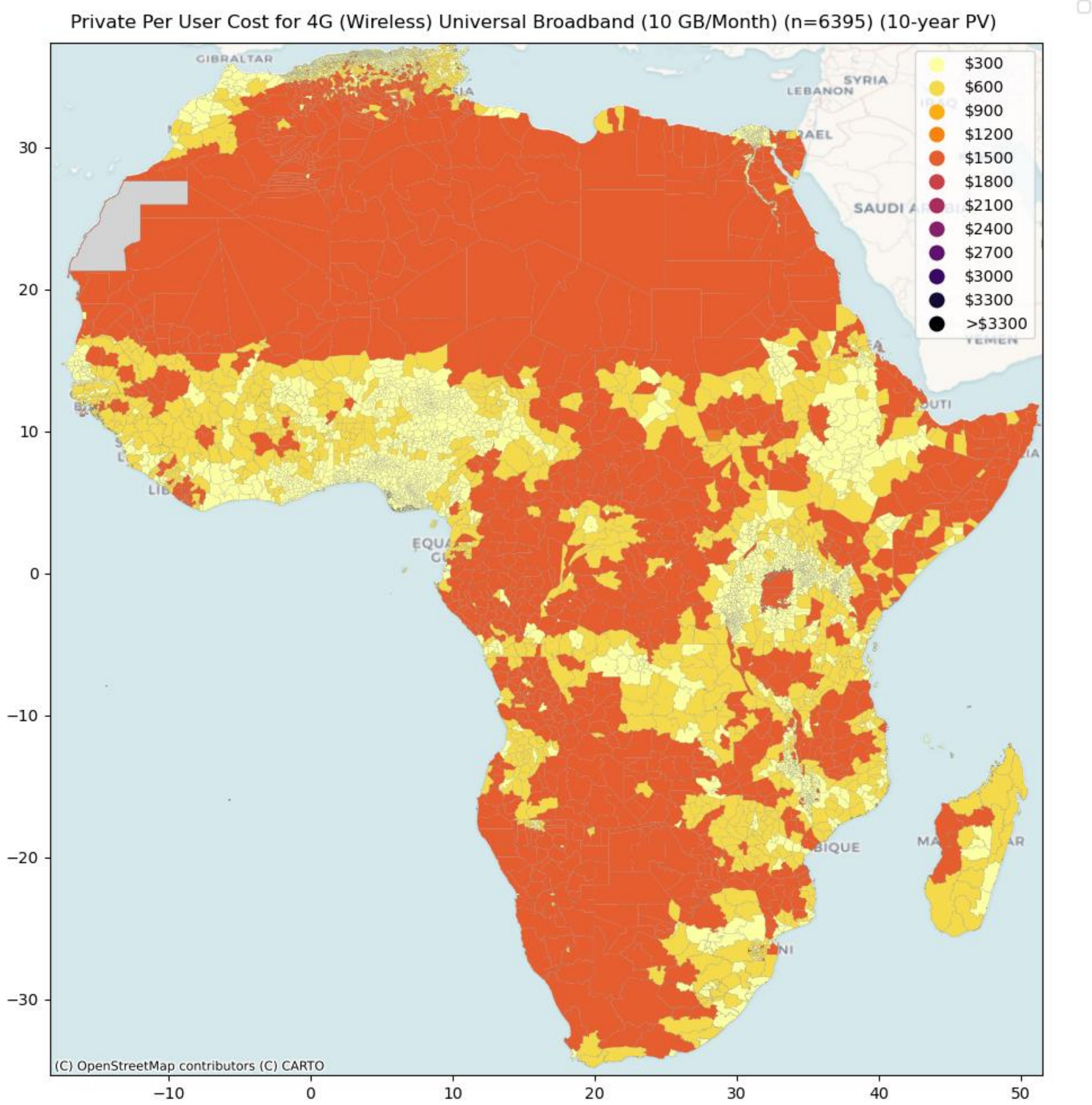


Figure S8 Per user government cost for universal broadband across the African continent (10 GB/Month)

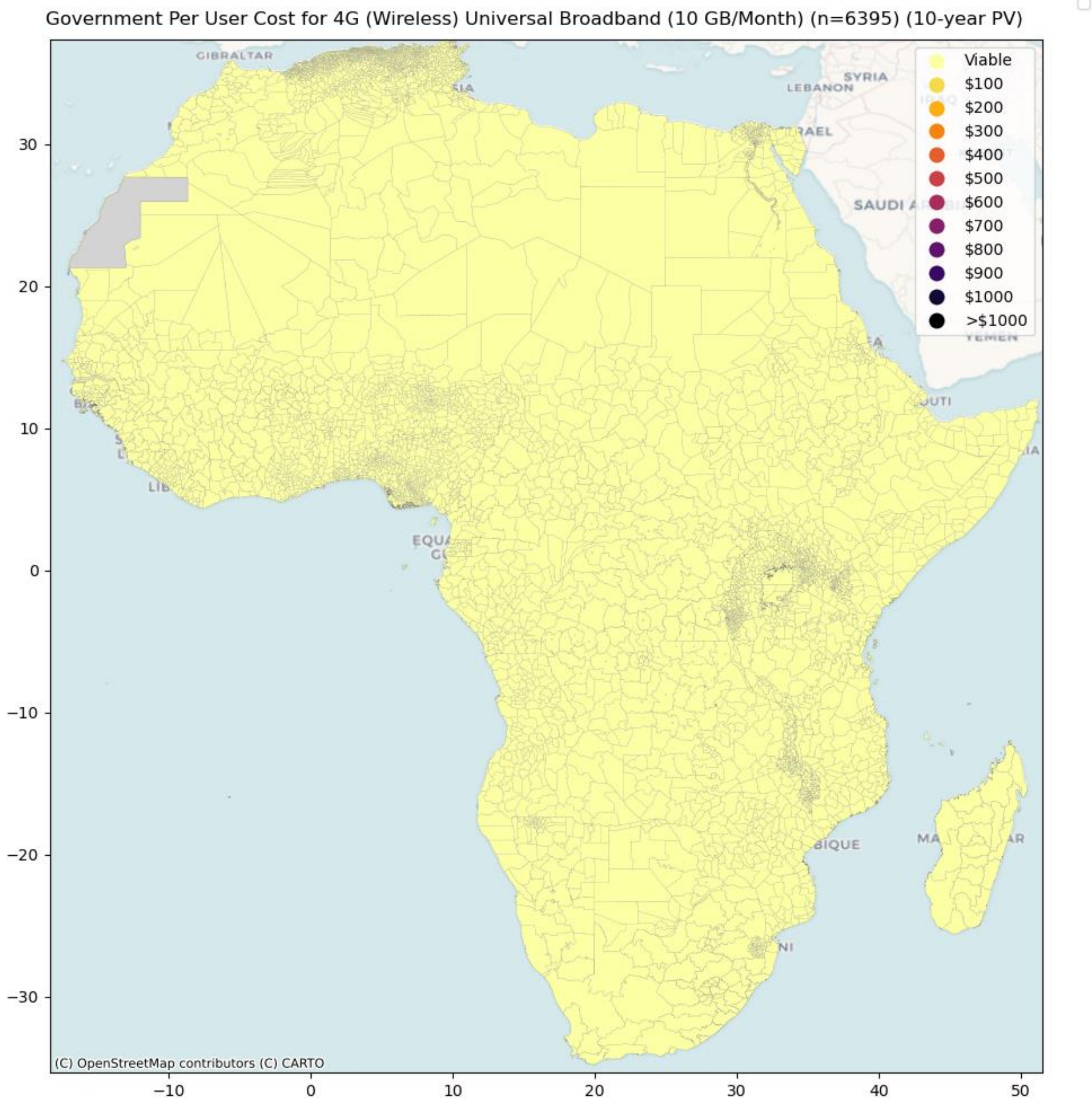
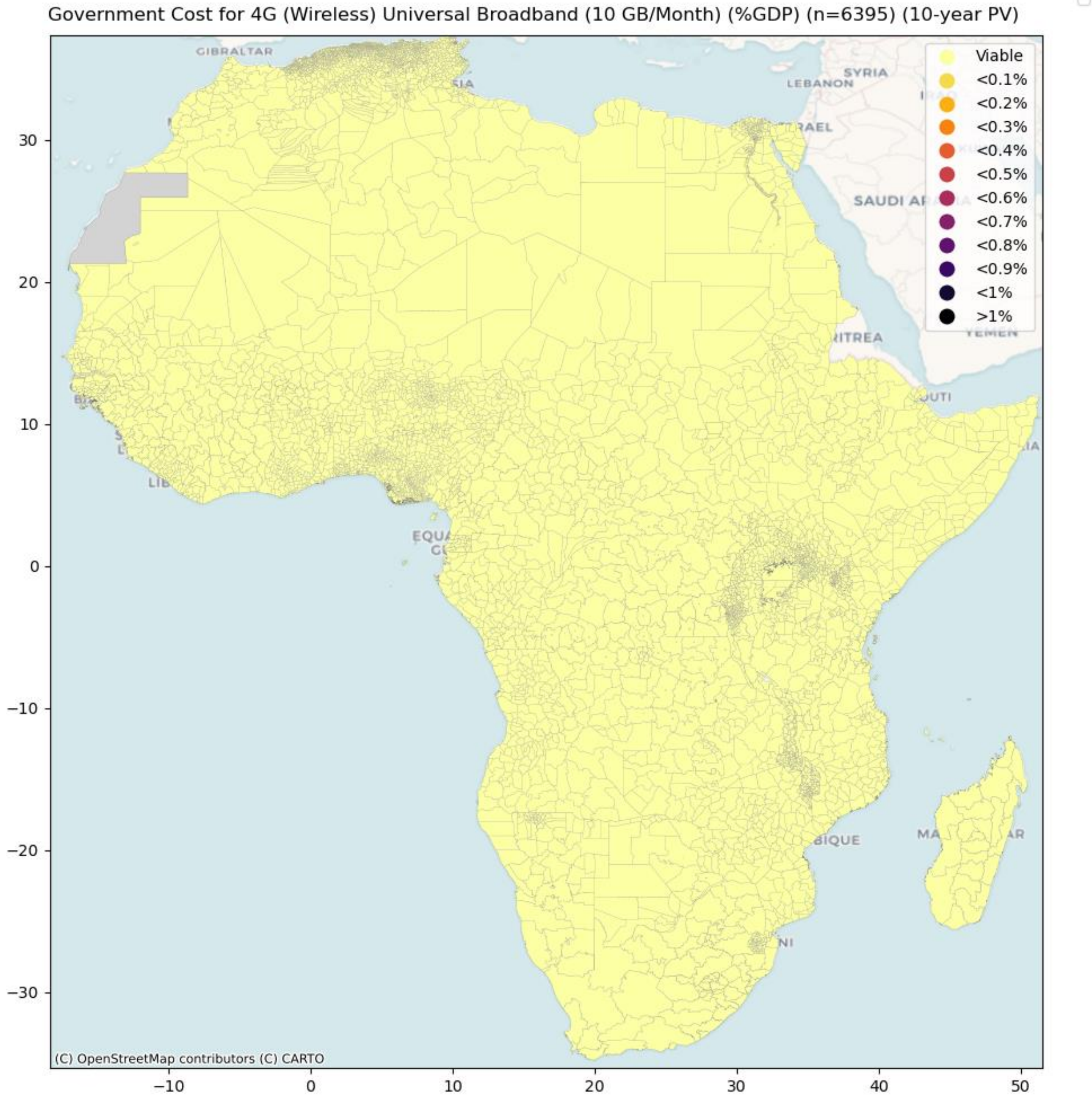


Figure S9 Government cost as a percentage of GDP for universal broadband (10 GB/Month)



Section S4 Decile Information

Table S1 Key statistics for decile segments

Decile	Decile Population Density Range (km^2)	Population	Area (km^2)	Population Density (km^2)
1	>1104	319,061,934	104325	3,058
2	541-1104	109,386,098	152883	715
3	367-541	74,513,593	167579	445
4	257-367	81,589,318	269783	302
5	171-257	130,382,386	632929	206
6	109-171	146,887,417	1089259	135
7	69-109	134,712,898	1565694	86
8	43-69	125,066,800	2291943	55
9	20-43	135,200,869	4482800	30
10	<20	101,396,214	19164210	5