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Abstract

The recent deployment of fibre-optic submarine cables (SMCs) in sub-Saharan Africa (SSA) raised the prospects for the digital economy expansion and the whole sub-continent take-off, but also exposed countries and populations to new sources of vulnerability. This paper provides empirical evidence on the ambivalent effect of SMC deployment on the digital divide in 46 SSA countries. On the one hand, results show that the laying of SEACOM, MainOne and EASSy cables in 2009-2010 has yielded a *three percentage points* increase in internet penetration rates. This is a huge increase, meaning that the deployment of these cables has almost doubled the penetration of Internet in the sub-continent's population. On the other hand, exogenous sources of telecommunication disruptions related to SMC laying – the country's exposure to SMC outages and digital isolation – are found to reduce internet and mobile penetration rates, to lower investments in ICTs, and to increase mobile-cellular tariffs and the wireline network instability. Therefore, while SMC arrival in SSA has reduced the digital divide, this divide would be lower if SSA countries were less digitally vulnerable.

JEL-Codes: F020, L960, O330, O180.

Keywords: ICT, internet, submarine cables, infrastructures, telecommunications, digital divide, Sub-Saharan Africa.

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1. Introduction

Information and communication technologies (ICTs), more particularly broadband Internet and mobile technologies, are general-purpose technologies that play an increasing role in the development process. By contributing to the emergence and dissemination of innovations in trade, agriculture, financial services and transportation, and to the modernization of public administrations, including tax administration, the digitization of the economy has raised the prospects of growth, employment and poverty reduction in sub-Saharan Africa (Aker & Mbiti, 2010; Andrianaivo & Kpodar, 2011; World Bank, 2016; Hjort & Poulsen, 2017). However, in the subcontinent, the expected dividends of digital technologies are slow to materialize and to benefit the whole population (World Bank, 2016). These low 'digital dividends' are seen as the result of the telecom infrastructure deficit (Schumann & Kende, 2013; Buys et al, 2009; Bates, 2014) and the poor governance of the telecommunication sector (Howard & Mazaheri, 2009; Akue-Kpakpo, 2013; Sutherland, 2014). Therefore, and despite the high penetration rate of mobile telephony in the continent, access to broadband in sub-Saharan Africa (SSA) primarily benefits the rich, the urban and the most educated (World Bank, 2016).

In Africa, the growth prospects from the digital economy expansion are nonetheless particularly important. According to the United Nations, the population of Africa is likely to increase from 1 billion inhabitants in 2014 to 2.4 billion in 2050, representing a quarter of the world's population, with the 15- to 24-year-old population rising from 200 million to more than 700 million in 2050. It is therefore on this continent that economic and social changes related to digital technology dissemination may be the deepest. The digital dividends for growth, employment and diversification in sub-Saharan African economies could, however, be significantly improved by an environment more conducive to the development of the telecommunications infrastructures (Ndulu, 2006; Schumann & Kende, 2013).

During the last decade, global connectivity has improved significantly with the worldwide deployment of more than 400 fibre submarine cables (SMCs) over the period 1990–2018, transmitting more than 99% of international telecommunications, the remaining being transferred by satellites. However, SSA remained relatively digitally isolated until 2009. Since then, the digital infrastructure has quickly unfolded, facilitating access and reducing the cost of broadband Internet and mobile telephony. Today, almost all coastal African countries are directly connected to the global Internet through SMCs. If the Internet penetration is still low in SSA compared to other developing regions, the strong dynamism of the mobile industry is an important lever for the development of the digital economy (ITU, 2016).

This paper brings new insights into the digital divide determinants in SSA by analysing how the maritime infrastructure deployment has affected the development of the telecommunication sector in the subcontinent. First, this paper contributes to the literature by providing novel evidence on the impact of different waves of SMC arrivals on ICT outcomes. Second, it highlights how the deployment of SMCs is associated with new sources of vulnerability for the telecommunication sector.

Digital vulnerability is defined as the risk for a country and its population of its access to telecommunication services being hindered by failures in its telecommunication networks. SMCs are vital infrastructures for the economy, and their recent laying in SSA has also increased the subcontinent's vulnerability to SMC outages. As an illustration, on 10th July 2009, the SAT-3 cable breakdown linking Europe to West and South Africa disrupted telecommunications in Benin, Togo, Niger and Nigeria. In May 2011, a new SAT-3 cable break caused by a boat anchor deprived Internet users in Benin, Togo, Niger, Burkina Faso and Nigeria for 10 to 15 days. More recently, in June 2017, the Main-1 cable broke 3000 km to the south of Portugal, disturbing the Internet in several countries in West Africa. In the same month, the anchor of a container ship accidentally cut the only SMC linking Somalia to the world Internet, depriving the country of the Internet for more than three weeks and causing economic losses estimated by the government of Somalia to be more than 10 million dollars a day. On March 30, 2018, damage to the African Coast to Europe (ACE) cable disrupted telecommunications in some 10 African countries, but more severely in six countries hosting only one cable (the ACE cable), which were unable to reroute and stabilize the telecommunication traffic.[2]

Moreover, in a core-periphery infrastructural setting, populations remote from vital infrastructure nodes are more exposed to telecommunication network failures (Gorman et al, 2004). In fact, the laying of SMCs has increased the spatial digital divide within the subcontinent and within countries[3]: between coastal and urban populations (the core) close to SMC landing stations and other key backbone infrastructures, benefitting from a faster and more stable telecommunication network, and isolated inland and rural populations (the periphery) with low infrastructure coverage and more exposed to telecommunication disruptions[4] (Gorman & Malecki, 2000). This pattern is explained by the lack of terrestrial infrastructure coverage and maintenance in many African states, and by the spatial hierarchy in telecommunications nodes favouring urban and coastal areas when disruptions occur (Malecki, 2002; Grubesic et al., 2003; Gorman et al, 2004; Grubesic & Murray, 2006). As a result, some countries with populations sparsely distributed over large or landlocked territories might exhibit a larger spatial digital divide after the laying of SMCs.

The contribution of the arrival of SMCs and related digital vulnerabilities – that is, the SMC exposure to shocks and digital isolation – to the development of the telecommunication sector is therefore examined. Estimations are conducted using telecommunication development variables aimed at reflecting five outcomes of the telecommunication sector: the Internet and mobile penetration rates as final outcome variables; the telecommunications tariffs, the telecommunication investments and the wireline network stability as intermediate outcome variables. The empirical approach is then developed in two steps. First, the impact of SMC deployment on Internet and mobile penetration rates is studied using a difference-in-differences (DID) estimation framework, looking at the evolution of penetration rates before and after different waves of SMC arrival on the subcontinent. Second, exogenous sources of digital vulnerability related to SMC deployment, and their effect on both final and intermediate outcomes are brought to light through a multivariate regression analysis.

DID estimations' results indicate that the deployment of the SEACOM, MainOne and EASSy cables in 2009 and 2010 was associated with a 3 percentage point increase in Internet penetration rates in SSA. This increase is huge since, taking sample average as a benchmark, the laying of these cables has almost doubled the penetration of Internet in the subcontinent's population. Then, the panel data analysis conducted on a sample of 46 African countries over the period 1994–2014 points to the negative impact of digital vulnerability on the development of the telecommunication sector. In particular, the results indicate: i) the negative effect of digital isolation and SMC exposure to shock variables on Internet penetration rates, mobile penetration rates and telecommunication investments; and ii) their positive effect on prepaid mobile-cellular connection tariffs and on the instability of the telecom network. Therefore, while the arrival of SMCs in Africa has boosted the digital economy, the digital divide would be lower if SSA countries were less exposed to SMC outages and if populations were less digitally isolated.

[2] These six countries – Sierra Leone, Mauritania, Liberia, Guinea-Bissau, Guinea and Gambia – displayed lower redundancy. See Meyer, D., "An Entire Country's Internet Was Cut Off for 2 Days After an Underwater Cable Broke", Fortune, April 9, 2018.

[3] Despite reducing the international digital isolation of many African states.

[4] A similar core-periphery pattern between coastal and inland areas is also observable in developed countries like the US (Gorman & Malecki, 2000).

Therefore, this paper provides new insights into the literature on the determinants of the digital divide in developing countries (Wallsten, 2005; Howard & Mazaheri, 2009), especially in SSA (Ndulu, 2006; Buys et al, 2009). First, this paper exploits a novel database on various features of SSA's telecommunication infrastructure network to analyse the development of ICTs in the subcontinent. Second, the paper quantifies the macro-level impact of SMC-laying on various telecommunication outcomes through a diff-in-diff econometric analysis. To my knowledge, such an approach has not yet been applied at the macro-level in SSA to a wide range of ICT variables. Third, and most importantly, this paper highlights both the benefits and the risks brought by SMC deployment, by providing evidence on the positive impact of SMC arrival in SSA and the negative impact of related vulnerabilities.

The next section presents a descriptive and comparative analysis of the contribution of the deployment of telecommunication infrastructures and emphasizes structural digital vulnerabilities that may arise therefrom. A DID approach is implemented in the third section to identify the impact of SMC deployment on the digital divide in SSA. Then, in the fourth section, a multivariate panel data analysis highlights how digital vulnerabilities related to SMC deployment affect telecommunication outcomes in the sub-region. The fifth section concludes the paper.

2. Maritime infrastructure deployment and digital vulnerability in sub-Saharan Africa

This section offers an overview of the interplay between the sub-Saharan African ICT sector performance and the expansion of international telecommunications infrastructures in the subcontinent. It also introduces the notion of digital vulnerability related to failures in the telecommunication infrastructure network. In fact, by connecting coastal African countries to the global digital economy, high-capacity telecommunication infrastructures make countries and populations more vulnerable to their eventual collapse.

2.1. Appraisal of the maritime telecommunication infrastructure deployment in sub-Saharan Africa

In 2015, sub-Saharan Africa (SSA) was connected to the world Internet through 15 SMCs, nine being spread over its west coast, and six over its east coast.[5] The laying of these cables has accelerated the development of the digital economy through greater access to affordable and fast Internet and mobile technologies, thereby improving the performance of firms (Cariolle et al, 2017; Paunov & Rollo, 2015, 2016), facilitating job creation (Hjort & Poulsen, 2017), increasing trade flows and foreign direct investments (Freund & Weinhold, 2004), and enhancing the quality of governance (Andersen et al, 2011; Asongu & Nwachukwu, 2016). The potential benefits of the deployment of such infrastructures are therefore very important (Röller & Waverman, 2001; Czernich et al, 2011).

The global network of submarine fibre-optic wires represents the first link in the Internet access chain, and the most efficient option for delivering international telecommunications services (e-mail, phone calls, video content, etc.). In the absence of submarine telecommunication cable (SMC), a country has two solutions for obtaining an international Internet connection: i) buying expensive and limited Internet bandwidth to a neighbouring country hosting a SMC (which necessitates being connected to

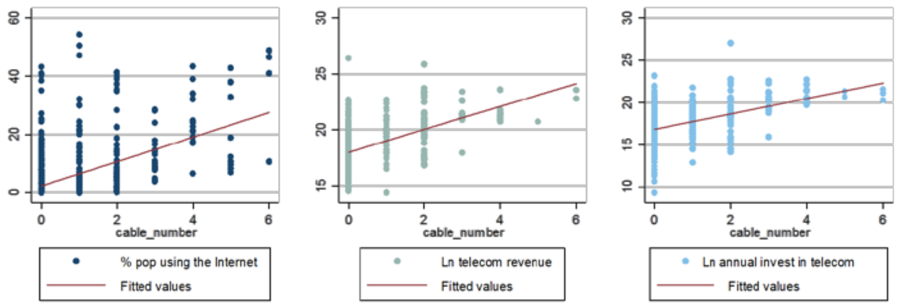
[5] **West-coast cables:** SAT3/SAFE (800 gigabits capacity), GLO-1 (2.5 terabits), ACE (5 terabits), MainOne (10 terabits), NCSCS (12.8 terabits), WACS (14.5 terabits), SAIL (32 terabits), SACS (40 terabits) and EllaLink (72 terabits) are expected in 2018. **East-coast cables:** SEAS (320 gigabits), TEAMs (1.2 terabits), LION 2 (1.3 terabits), EASSy (10 terabits), Seacom (12 terabits) and DARE (60 terabits) are expected in 2018.

that country by a terrestrial wireline infrastructure), or ii) buying Internet bandwidth – which is costly, slow and limited – to communication satellites.

SMC deployment is therefore the first step towards global Internet access, and is a subsequent catalyst for terrestrial infrastructure investments, by making them more profitable (Schumann & Kende, 2013). The increase in the number of SMCs connecting countries to the global Internet enlarges the total bandwidth available to Internet users, reduces the cost of Internet services, intensifies competition in the telecom sector, improves Internet redundancy and reduces the impact of cable outages (Weller & Woodcock, 2013; Schumann & Kende, 2013; Telegeography, 2016).

To illustrate the interplay between the deployment of SMCs and some telecommunication outcomes, the graphical correlation between the number of SMCs and three common metrics of the Internet economy's dynamism in SSA is illustrated in Figure 1. This graph demonstrates a positive correlation of SMC deployment with Internet penetration rates, and with the revenues and investments of the telecom sector.

Figure 1. SMC deployment and the telecom sector, sub-Saharan Africa, 1990–2014.



Source: Raw data from ITU (2016) and Telegeography (2016).

2.2. SMC deployment and digital vulnerability in sub-Saharan Africa

Digital vulnerability is defined as the risk for a country and its population of access to telecommunication services being hindered by failures in its telecommunications network. These failures may result from the undercapacity or gradual obsolescence of the telecommunications infrastructure network, as well as its exposure to recurring external shocks and internal failures (server breakdowns, SMC outs, closing of data centres of Internet exchange points), power outages and cyber-attacks.

This paper focuses primarily on digital vulnerabilities accompanying the deployment of SMCs.[6] Once a country is connected to the global Internet through SMC, countries are exposed to two structural interrelated sources of digital vulnerability, independent of policy: i) their exposure to SMC outages, and ii) the digital isolation resulting from the geographical distance to SMC landing stations, and making isolated countries and remote populations even more exposed to telecommunication failures (Grubesic & Murray, 2006; Grubesic et al, 2003).

The exposure to SMC outages

The recent and massive laying of fibre SMCs in SSA is considered a major driver of progress for mobile and Internet penetration, and for the digital economy's expansion as a whole. However, SMC

[6] And therefore it does not address the question of Internet exposure to power outages and cyber-attacks, to which the analysis would be equally applicable and informative (Grubesic & Murray, 2006).

deployment over the subcontinent has also increased its vulnerability to SMC outages, resulting from two principal sources (Carter et al, 2009; Clark, 2016):

- Human activities: mainly maritime activities (fishing nets, anchors), which are the most common cause of outage, but also acts of piracy and sabotage.
- Natural events: such as seismic shocks, typhoons, floods, volcanic eruptions and turbidity currents, which are the main cause of multiple simultaneous SMC breaks.

First, SSA has a recent experience of recurrent cable outages. Table 1 below presents a list of SSA countries affected by cable breaks between 2008 and 2017, based on a study of the information available on the Web (see details in Online Appendix B). Second, SSA's maritime infrastructure is also exposed to seismic risk.[7] In fact, seismic activity is a major cause of both direct and indirect cable breaks by provoking turbidity currents, landslides and tsunamis (Soh et al, 2004; Carter et al, 2009; Clark, 2016; Aceto et al, 2018; Yincan et al, 2018). Compared to other sources of SMC outages, seaquake-induced cable breaks may lengthen the time needed to repair cables by inducing simultaneous multiple outages (Palmer-Felgate et al, 2013; Yincan et al, 2018), and may therefore be costlier for the economy. I document this exposure in SSA in Table 2, exploiting information on the location, timing, frequency and intensity of seaquakes, to calculate the annual frequency of seaquakes that occurred within a radius of 500 km from SSA's SMC landing stations between 1995 and 2014.[8] The data indicate that East Africa and, to a lesser extent, Central Africa are two areas exposed to the risk of seaquake-induced cable outages.

The increasing occurrence of cable cuts, induced by maritime activities or natural hazards, and their damaging effects on African economies hence represent a major concern for digital ecosystems. This concern is even stronger in a number of low-resilient African countries, which rely on just a few SMCs to gain access to international communications. In fact, in addition to the direct costs of repairing damaged cables for telecoms operators, amounting to millions of dollars depending on the cable repair frequency and length, there are indirect economic costs, rising to tens or hundreds of millions of dollars related to (Widmer et al, 2010; Clark, 2016; Aceto et al, 2018):

- The reporting of repair costs and insurance costs on communication tariffs and its consequences for Internet and mobile penetration;
- The rerouting of the traffic towards more expensive cable paths and its consequences for communication speed, volume and tariffs;
- The disorganization of global manufacturing chains and Internet-related service provision (e.g. financial services).

Moreover, these direct and indirect costs are increased by delays in cable repairs. According to Palmer-Felgate et al (2013), these delays vary significantly among maintenance areas and countries, and mostly result from multiple outages induced by natural events such as earthquakes or typhoons, ships engaged in prior repairs (likely induced by multiple outages), repair permit acquisition delay or operational issues (Borland, 2008; Yincan et al, 2018).

Therefore, SSA is exposed, like many other developed and developing areas, to SMC breaks that could induce substantial social and economic losses. This exposure is particularly problematic for SSA, given the relatively low number of SMCs connecting countries in the subcontinent, which

[7] Though to a much lesser extent than Asian or Caribbean countries (see Cariolle et al, 2017).

[8] The focus placed on seaquakes is explained by the fact that earthquakes cause damage to the whole economy and therefore not only to telecommunication networks. To better identify the impact of this exposure variable, we only considered seaquakes above 5 on the Richter scale. This lower bound has been chosen in accordance with Soh et al (2004), who found that in the eastern part of Taiwan cable breaks occurred following earthquakes ranging from 5.0 to 6.0 on the Richter scale.

displays lower resilience to SMC outages than other developing regions. In the following subsection, the geography of SSA – consisting of many large, landlocked and rural countries – is identified as an additional factor of digital vulnerability.

Table 1. Occurrence of sub-Saharan African cable breaks, reported on the Web

Country/region	year	# breaks	Country/region	year	# breaks
West Africa	2017	1	Niger	2011	1
East Africa	2016	1		2009	1
	2010	1	Nigeria	2015	1
South Africa	2016	1		2012	1
Benin	2011	1		2011	1
	2009	1		2009	1
Burkina Faso	2011	1	Rwanda	2012	1
Burundi	2012	1	Somalia	2017	1
Cameroon	2017	1	Tanzania	2012	1
Congo Rep.	2017	1		2010	1
Djibouti	2008	1	Togo	2011	1
Gabon	2015	2		2009	1
Kenya	2012	1	Uganda	2012	1
	2010	1	Zambia	2008	1
				TOTAL	**24**

Source: author. Most data are gathered from https://subtelforum.com/category/cable-faults-maintenance/., cross-checked and complemented with keyword-based Internet searches.

Table 2. Annual seaquake frequency above 5 on the Richter scale in SSA, 1995–2014

Country	Year	Seaquake freq.	Country	year	Seaquake freq.
Angola	2001	1	Kenya	2005	1
RDC	2001	1	Madagascar	2013	1
Congo, Rep	2001	1	Sudan	1996	1
Comoros	1995	2		2001	1
	2000	1		2009	1
	2002	1		2010	1
	2005	2		2013	2
	2007	3	Somalia	1997	3
	2008	3		1998	2
	2010	1		2000	3
	2012	2		2001	6
Cap Verde	1998	1		2002	3
Djibouti	1997	2		2003	2
	1998	2		2004	2
	2000	2		2005	2
	2001	1		2006	6
	2002	1		2007	2
	2003	1		2008	3
	2004	1		2009	6

2005	1		2010	27
2006	1		2011	4
2007	2		2012	2
2008	2		2013	2
2009	4	Seychelles	1995	1
2010	25		2003	1
2011	3	Tanzania	2005	3
2012	1		2008	3
2013	2		2010	1

Source: author. Data retrieved from Telegeography and the Northern California Earthquake Data Center.

Distance to SMC, digital isolation and the digital divide

In 2016, most coastal developing countries were connected to the global economy by SMC. However, the arrival of SMCs in Africa has only reached a limited share of the African population – mostly rich, educated urban and coastal people – so that the digital divide is more striking at the subcontinent or country levels rather than at the global level. As a result, inland infrastructure deployment is considered one of the major challenges for the telecom industry and the whole economy in low-income countries, especially SSA countries (Ndulu, 2006; Towela & Tesfaye, 2015; Bates, 2014; Weller & Woodcock, 2013).

Some studies have stressed how locations that are geographically isolated or remote from the telecommunication infrastructure are more vulnerable to infrastructure outages, including large telecommunication disruptions. Grubesic and Murray (2006) show that in countries where telecommunication assets are concentrated in just a few places, telecommunication network cascading failures following infrastructure collapses are more likely to occur. They also point out that locations that are distant from vital telecommunication nodes are particularly exposed to telecommunication disruptions. Moreover, Grubesic et al (2003) show that digitally isolated locations are slower to recover after network disruptions, and therefore incur larger economic and social costs from the experience of telecommunication shutdowns. As a result, the geography of many SSA countries – characterized by vast and often landlocked territories, a large rural population, and infrastructures concentrated in capital cities and coastal areas – increases the likelihood and the negative impact (in terms of geographical coverage and persistence) of telecommunication disruptions following infrastructure outages (Gorman & Malecki, 2000; Gorman et al., 2004).

Digital isolation in some areas therefore depends on both structural factors, such as the geographical fragmentation of the continent, landlockedness, the size of the country, the altitude and the spatial distribution of the population; and policy-related factors, such as the quality of regulation and the extent of public and private investment in the telecom sector (Jensen, 2006; Sutherland, 2014). The study of the geographic determinants of digital isolation, by their exogenous nature, is of particular interest here. For this purpose, three distance variables have been computed to proxy digital isolation:

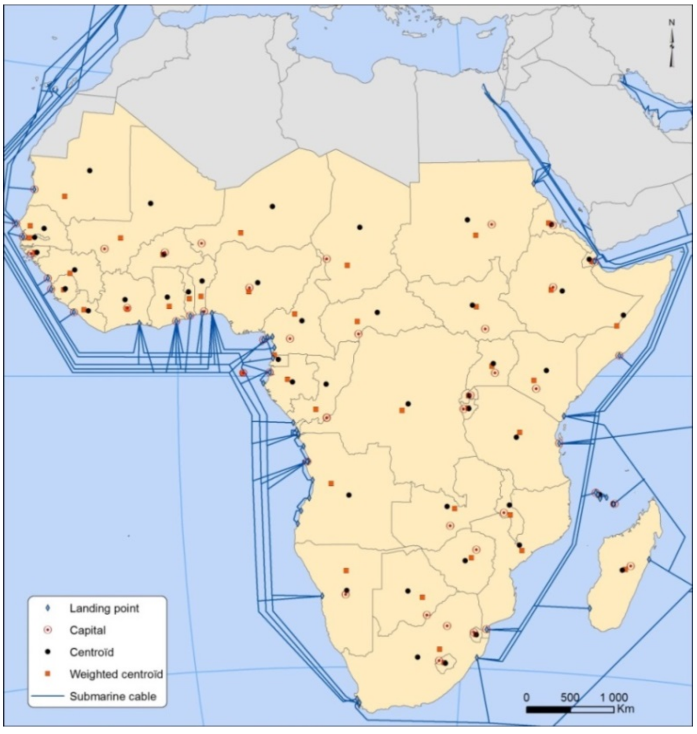
- The **geographic centroid distance to SMC**, i.e. the distance between the geographic centroid and the closest SMC landing station.[9] This geographic distance is the bird's-eye distance required for the deployment of the backbone telecom infrastructure that minimizes the infrastructure gap for any random locations in the territory.

[9] When one country does not host an SMC, the distance to the closest SMC landing station among neighbour countries is calculated.

- The **capital distance to SMC**, i.e. the distance between economic capitals and the closest SMC landing station. This capital distance is the bird's-eye distance required for the deployment of the backbone telecom infrastructure to reach the principal demographic and economic centre.
- The **demographic centroid distance to SMC**, i.e. the distance between the geographic centroid weighted by the spatial distribution of the population (denoted as the demographic or weighted centroid) and the closest SMC landing station. This demographic distance is the bird's-eye distance required for the deployment of the telecom infrastructure that minimizes the average infrastructure gap with the whole population. This distance is the result of both the geographic distance and the capital distance previously mentioned.

The geographical distance to SMCs reflects the geographical handicaps faced by large and/or landlocked countries in bringing ICTs over the whole territory. The capital and demographic distance both reflect the geographical handicap faced by large, landlocked and rural countries in bringing ICTs to their population. The longer these distances, the more likely is the digital isolation of the population. The map in Figure 2 below gives an idea of these distances in SSA by plotting the countries' centroid, weighted centroid and capital against SMC landing stations.

Figure 2. Capitals, geographic and demographic (weighted) centroids and SMC landing stations in sub-Saharan Africa in 2017.

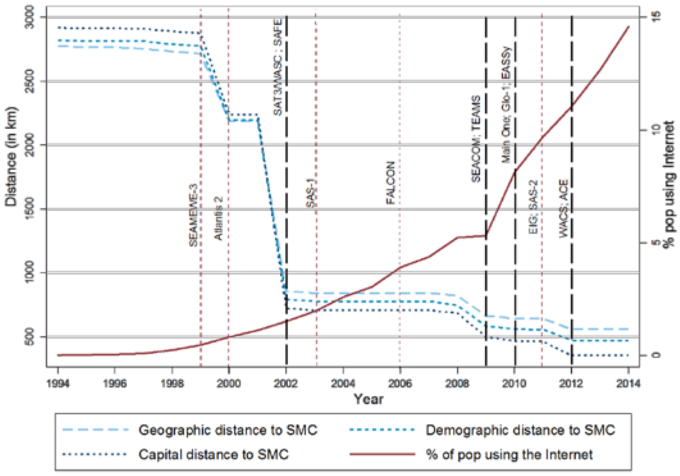


Source: author.

Figure 3 below represents the different waves of SMC deployment together with the evolution of the geographic, capital and demographic distances to the closest SMC landing station, and the evolution of the average Internet penetration rate in SSA. Years associated with regional SMC waves (connecting more than four countries to the global Internet) are identifiable by long dashed lines. This graph indicates that the waves of SMCs track the decreasing trend in the distance variables, and the increasing trend in the subregional Internet penetration rate. Notably, in 2009 and 2010, the arrivals of the SEACOM, MainOne, and EASSy regional cables are associated with a striking regime shift in the average Internet penetration rate's evolution.

In summary, the rapid and worldwide deployment of SMCs had a significant impact on the development of the telecommunications sector in SSA, triggering or boosting the ‘digital revolution’ in the subcontinent. Coastal countries in SSA are now almost all connected to the global Internet by SMC, but the digitization of the subcontinent is facing two main structural factors of digital vulnerability. On the one hand, African countries are exposed to the risk of SMC outages, with a dramatic impact on the development of the telecommunications sector and the economy as a whole. On the other hand, many large, landlocked or rural African countries, whose populations are distant from SMC, may suffer from greater digital isolation and be deprived from affordable and stable access to ICTs.

Figure 3. Declining average distances to SMC landing stations and waves of transcontinental SMC deployment in SSA.



Source: author. Long dashed vertical lines: arrival of a transcontinental regional SMC (connecting more than two countries). Short dashed vertical lines: arrival of a transcontinental local SMC, connecting at least four African countries.

3. Empirical analysis

Using a panel dataset covering about 46 African countries over the period 1990–2014, this empirical analysis tries to unravel the contribution of the submarine telecom infrastructure to telecommunication sector outcomes by studying the impact of the deployment of SMCs on the one hand, and the impact of new digital vulnerabilities related to their deployment on the other.

3.1. Estimating the impact of SMC deployment

In a first step, a difference-in-difference (DID) estimation framework (Card & Krueger, 1994; Heckman et al, 1998) is adopted to study the impact of different waves of SMC arrivals on final telecommunication outcome variables. Among the different waves of SMCs that connected SSA to the global Internet, only SMCs deployed regionally, i.e. SMCs connecting at least four sub-Saharan African countries together or to another continent, were considered. In fact, SMCs are often deployed regionally because of the small market-size of many SSA countries, and because of the high fixed-cost of this infrastructure, requiring public and private telecom operators and investors from various neighbouring countries to share them (Jensen, 2006). By contrast, the laying of SMCs connecting a smaller number of countries could be influenced by national policy-related factors rather than aggregate regional considerations, and therefore make the treatment endogenous. Among the various waves of regional SMC arrivals (see Figure 8) in SSA, the following regional cables are considered:

1. the SAT3, WASC, SAFE cables deployed in 2002, connecting South Africa, Angola, Gabon, Cameroon, Nigeria, Benin, Ghana, Ivory Coast, Senegal and Mauritius to Asia and Europe.
2. the SEACOM cable deployed in 2009, connecting South Africa, Tanzania, Kenya and Djibouti to Asia and the MENA region.
3. the MainOne and EASSy cables deployed in 2010, respectively connecting the Senegal, Ivory Coast, Ghana and Nigeria to Europe, and South Africa, Madagascar, Comoros, Tanzania, Kenya, Somalia, Djibouti and Sudan together.
4. the WACS and ACE cables deployed in 2012, connecting South Africa, Namibia, Angola, the RDC, the Congo, Cameroon, Nigeria, Togo, Ghana, Sierra Leone, Ivory Coast, Cap Verde, Liberia, Benin, Guinea, Gambia, and Mauritania to Europe.

Once the treatment is identified, the following equation is estimated:

$$ICT_{i,t}^{j} = \delta_0 + \delta_1 D_t + \delta_2 D^j + \delta_3 D_t^j + \delta_4 X_{i,t} + \varepsilon_{i,t}^{j} \qquad (1)$$

where *j* indexes the treated and untreated groups, with j=1 for the treatment group (country *i* has been connected to the global Internet by an SMC at time *t*) and j=0 for the control group (country *i* has not been connected to the Internet by an SMC at time *t*). ICT_{it} is the final telecommunication outcome variable, detailed in the next subsection. D_t is a dichotomous time variable equal to one after the SMC arrival and zero before the SMC arrival, D^j is a dichotomous variable equal to one if country *i* is concerned by the SMC arrival and zero otherwise, and D_t^j is a dichotomous variable equal to one when country is treated and zero otherwise. $X_{i,t}$ is a vector of control variables, detailed in the next subsection, and $\varepsilon_{i,t}^{j}$ is an error term. Under the assumption that $E\left(\varepsilon_{i,t}^{j} \middle| D_t^j\right) = 0$, the parameter δ_3 is the coefficient identifying the causal effect of the treatment – the SMC arrival – on telecom outcomes. This causal effect is obtained by calculating the DID equal to the change in mean Internet penetration rates for the treatment group minus the change in mean Internet penetration rates for the control group. The parameter δ_1 captures how both groups are affected over time by the SMC arrival, and the parameter δ_2 captures the time-invariant difference in Internet penetration rates between the treatment and control groups.

Moreover, DID estimations are conducted over different samples of African countries, to address possible selection and omitted variable biases. First, South Africa and Nigeria are excluded because regional SMCs might have been deployed to connect these major demographic and economic centres to the rest of sub-Saharan African countries, which therefore could make the treatment endogenous. Second, coastal countries located on regional SMCs' path but not connected to them are excluded for the same endogeneity concern, as the fact of not hosting a regional SMC may be the result of bad national policies or institutions.[10] Third, landlocked countries are also excluded because they cannot directly host SMCs. This geographic feature makes them particularly dependent on their neighbouring coastal countries receiving SMCs, so that the treatment might act in a different way in these countries. Fourth, we conduct DID estimations over the 2002–2012 subperiod and the whole 1990-2014 period. Nevertheless, the years 2002–2012 represent the subperiod of interest since it excludes the laying of other regional SMCs preceding or following the SMC under study.[11]

[10] In some countries, governments may delay or refuse SMC arrival in order to protect public or private monopolies in the telecom domestic market.
[11] Between 2002 and 2012, there have been three SMCs with a minor impact on SSA's, i.e. connecting only one SSA country (either Sudan or Djibouti): the SAS-1 and 2, the Falcon, and the EIG.

3.2. Estimating the impact of digital vulnerability

In a second step, a multivariate regression analysis of the impact of new digital vulnerabilities resulting from SMC deployment on the telecommunication sector is conducted by applying the *within* fixed-effect estimator to the following specification:

$$ICT_{i,t} = \alpha_0 + \alpha_1.X_{i,t} + \alpha_2.SMC_{i,t} + \alpha_3.VUL_{i,t} + \theta_i + \rho_t + \omega_{i,t} \quad (2)$$

where $ICT_{i,t}$ is the telecommunication sector's final or intermediary outcome variable in country *i* and year *t*, $X_{i,t}$ is a vector of control variables, and SMC_{it} and VUL_{it} are variables of SMC deployment and of structural sources of digital vulnerability, respectively. θ_i is the country fixed effect and ρ_t is the time fixed effect controlling for unobserved fixed country and time heterogeneity, and $\omega_{i,t}$ is an error term. Dependent and independent variables are detailed in the next subsection.

In this panel estimation framework, variables of interest are digital vulnerability variables (VUL_{it}) because of their structural and exogenous nature. Infrastructure deployment (SMC_{it}) variables are included as controls to avoid omitted variable bias.

3.3. The data

The data used in the empirical analysis are detailed in this section. Data sources, definitions, and treatment are presented in Online Appendices A and B, while descriptive statistics and cross-correlation coefficients between variables are presented in Appendix A.

Telecommunication sector outcomes (ICT_{it})

Final outcome variables are used as dependent variables in DID estimations (eq. (1)), while both final and intermediary outcome variables are used in the multivariate regression analysis (eq. (2)). The development of the telecommunication sector (ICT_{it}) is therefore approximated by three final outcome variables:

- **Final outcome 1: the Internet penetration rate** in the population, that is, the share of Internet users in the population.
- **Final outcome 2: the mobile penetration rate**, that is, the number of mobile cellular subscriptions per 100 inhabitants.
- **Final outcome 3: the share of households with Internet connection**. This Internet penetration variable is more restrictive since it confines Internet access to home-based fibre Internet.

The Internet penetration rate in the population is used as the main final outcome variable because it better reflects Internet usage in Africa (access to the Internet via Internet cafés and through mobile phones) than the share of households with an Internet subscription, which depends on the wireline infrastructure overage, often lacking in SSA. We also use an indicator of mobile penetration as a final telecommunication outcome variable because the Internet penetration rate in SSA relies heavily on mobile phone penetration rates.

In multivariate regression analyses, specified in equation (2), we also use as dependent variable three intermediary outcome variables that further the comprehension of the channels linking digital vulnerabilities to final telecommunication outcomes. In fact, digital vulnerability variables may widen the digital divide by increasing telecommunication tariffs, by reducing the telecommunication sector's capacity for providing quality services and by increasing the telecommunication networks instability:

- **Intermediary outcome 1: telecommunication tariffs**, proxied by the mobile cellular prepaid connection charge (in USD and logarithm).[12]
- **Intermediary outcome 2: the telecommunication sector dynamism**, proxied by the total annual investments in the telecommunication sector (in USD and logarithm).[13]
- **Intermediary outcome 3: the telecommunication network instability**, proxied by the annual number of faults per 100 fixed phone lines (in logarithm). This variable is of particular interest for the analysis since one direct consequence of digital vulnerabilities is the instability of networks.[14]

Digital vulnerability variables (VUL_{it})

Variables of digital vulnerability, discussed in the previous section, and explaining the development of the digital economy, are as follows:

- **The experience of SMC outages:** this shock variable is the annual number of SMC outages that have affected Internet traffic in sub-Saharan African countries, as described in Table 2.
- **The risk of SMC outages induced by seismic activity:** this risk variable is the annual frequency of seaquakes above 5 on the Richter scale that occurred within a 100 km, 500 km and 10,000 km radius from an SMC landing station, alternatively.
- **Digital isolation:** alternatively approximated by the geographic, capital or demographic distances to SMC landing stations.

Control variables (SMC_{it}, X_{it})

Control variables included in equations (1) and (2) are the logarithm of GDP per capita, the share of the population between 15 and 64 years old, the share of the urban population, the degree of democracy, the secondary education index, the share of the population with access to electricity[15], and the number of Internet exchange points to proxy the terrestrial infrastructure deployment[16]. In DID estimations of equation (1), I also control for being landlocked and the country's area.

In equation (2), a set of SMC-related variables (SMC_{it}) is also included to avoid omitted-variable bias. These controls are the number of SMCs, the total number of operators/investors sharing the ownership of SMC by country, and the number of years passed since the arrival of the first fibre-optic SMC.

4. Empirical results

This section presents difference-in-differences (DID) estimations of SMC arrival on the telecom sector final outcomes (equation (1)). Then, multivariate estimations of equation (2) are conducted to

[12] This mobile prepaid tariff variable is preferred to other tariff variables such as mobile monthly subscription charge because of better data availability, and because it better reflects mobile phone usage in SSA.

[13] We chose the investment variable to proxy the telecom sector performance rather than the telecommunication sector's revenue, because the latter may reflect operators' and ISPs' higher revenues derived from a monopoly position, which often leads to low service quality, high tariffs and infrastructure under-exploitation (Sutherland, 2014).

[14] However, this variable does not fully reflect the overall network instability since faults that are not the responsibility of public operators are not recorded (see Online Appendix A).

[15] As this last variable is documented sporadically, missing data are replaced by five-year moving averages. When a five-year average cannot be calculated, we use the previous five-year average value.

[16] Internet exchange points are physical Internet hubs that permit the reduction of communication latency, by promoting direct interconnections between countries, and the saving of bandwidth through an efficient allocation of local, regional and international traffic. IXPs also allow the sharing of Internet and other communications traffic at low cost, which in turn reduces the cost of telecommunication services. Therefore, the IXP network is a central element for the development of local and regional Internet ecosystems (Malecki, 2002; Weller & Woodcock, 2013; OECD, 2014).

highlight the interplay between different sources of digital vulnerability and the development of the telecom sector in SSA.

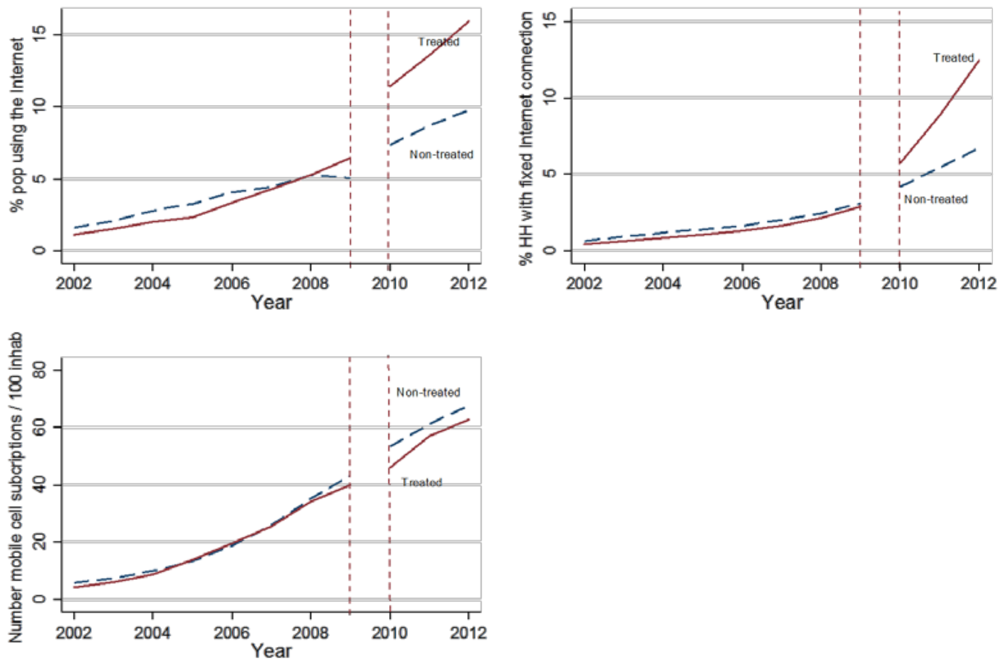
4.1. Impact of SMC arrivals on ICT penetration rates in SSA: DID estimations

The DID approach followed in this paper considers the various waves of SMC arrivals in SSA as different treatments likely to impact on the development of the telecom sector in the subregion.

SMC regional arrivals and the parallel trend assumption

One critical assumption of the DID estimator is the parallel trend assumption, which requires outcome variables to follow parallel trends in the absence of treatment, in our case, SMC arrivals. Without information on what would have happened without treatment, one common practice is to check the existence of a parallel trend before the treatment. To check whether this assumption holds for telecommunication outcomes (TIC_{it}), Figures 4 plots the co-evolution of these outcomes for treatment and control groups related to waves 2 and 3 taken together, between 2002 (after wave 1) and 2012 (before wave 4).

Figure 4. Trend comparison of telecom outcomes between treatment and control groups – SEACOM/EASSy/MainOne (2009-2010)



A visual inspection of this graph supports that these two waves of SMC deployment are a relevant experiment for a DID analysis, as i) Internet penetration rates of treated and non-treated groups exhibit parallel but also same-level trends before the treatment, and ii) these trends greatly diverge after the treatment. By contrast, these waves of SMCs do not seem to have impacted on the penetration of mobile phones, which is not very surprising since the mobile phone in SSA has in some way leapfrogged the deployment of infrastructures (Aker & Mbiti, 2010). The following DID analysis will therefore focus on the impact of waves 2 and 3 taken together on Internet penetration rates. [17]

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[17] DID estimates are also robust when considering wave 2 alone as the treatment (see Online Appendix C). SEACOM (wave 2) and the MainOne/EASSy's (wave 3) deployment are considered as one single treatment, because they occurred from one

DID estimations

DID estimations are run over an original sample of i) 46 SSA countries (sample A), ii) the original sample excluding South Africa and Nigeria (sample B), iii) the original sample excluding South Africa and Nigeria, as well as all coastal countries unserved by regional SMCs but located on its path (sample C), and iv) excluding landlocked countries (sample D).

Estimates are reported in table 3 and show that the SEACOM/EASSy/MainOne cables had a strong, positive and significant impact on Internet penetration rates.[18] First, results from the original sample A show that these waves led to an approximate 5 percentage point increase in the share of the population using the Internet, and that the resulting estimates are not affected by the estimation period. Second, the impact of SMC deployment remains positive and significant when South Africa, Nigeria and unserved coastal countries are excluded (samples B and C), but associated to a 3 percentage point increase in the share of the population using the Internet. This suggests either the existence of a heterogeneous effect of SMC arrival among African countries, or a sample bias inflating estimated relationships. In any case, this is a huge increase since the average Internet penetration rate in the sample is around three percent over 1990-2014 (Appendix A), maximum five percent before the treatment (figure 4). Third, the estimate is still positive and significant when the sample is limited to African coastal countries, lying within the same range as with the original sample A, suggesting that SMC arrivals on the African littoral also had a strong impact in landlocked countries, probably by reducing their international digital isolation. Fourth, the impact of SMC deployment on the share of households with Internet connection is significant and lies within the same amplitude as previous estimates.

To conclude this first empirical section, DID estimations indicate that the arrival of SMCs in 2009 and 2010 had a robust, significant and positive impact on Internet penetration rates in SSA. The next section furthers the analysis of the consequences of SMC arrivals for the Internet economy by highlighting the impact of structural sources of digital vulnerability related to their deployment.

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year to another and may have a confounding effect on ICT outcomes' evolution. The co-evolutions of these outcomes related to waves 1, 2 and 4 are reported in Appendix B but are not considered in the following analysis because waves 1 and 4 seem to have had a low influence on telecommunication outcomes, and because wave 2 shows divergent pre-treatment trends of the HH Internet penetration variable. In contrast to other cables, ACE has been slowly expanding over time, which may explain why telecommunication outcomes are not very responsive to its deployment.

[18] DID estimations considering the mere SEACOM deployment in 2009 as treatment, are reported in Online Appendix C. The resulting estimates are very close to those reported in table 3.

Table 3. DID in Internet penetration rates, before and after waves 2 & 3 (SEACOM- MainOne-EASSy)

	DID parameters (δ_3)	# observations	# treated/control obs	R-squared
	Period 2002–2012			
	% population using the Internet			
Sample A: 46 SSA countries	5.054*** (5.64)	360	88/272	0.64
Sample B: SSA excl. ZAF and NGA	2.659*** (3.05)	342	70/272	0.54
Sample C: ZAF, NGA, & unserved coastal countries excl.[a]	2.931*** (2.88)	267	61/206	0.55
Sample D: SSA excl. landlocked countries	5.202*** (4.87)	235	88/147	0.66
	% HH with Internet connection			
Sample A: 46 SSA countries	3.839*** (5.92)	305	86/219	0.63
Sample B: SSA excl. ZAF and NGA	3.095*** (4.99)	287	68/219	0.58
Sample C: ZAF, NGA, & unserved coastal countries excl.[a]	3.596*** (5.14)	226	59/167	0.63
Sample D: SSA excl. landlocked countries	3.912*** (4.74)	209	86/123	0.63
	Period 1990–2014			
	% population using the Internet			
Sample A: 46 SSA countries	5.655*** (9.02)	720	180/540	0.65
Sample B: SSA excl. ZAF and NGA	2.947 *** (4.92)	681	141/540	0.58
Sample C: ZAF, NGA, & unserved coastal countries excl.[a]	3.277*** (4.71)	526	124/402	0.60
Sample D: SSA excl. landlocked countries	5.903*** (7.73)	472	180/292	0.65
	% HH with Internet connection			
Sample A: 46 SSA countries	3.886*** (6.39)	339	96/243	0.62
Sample B: SSA excl. ZAF and NGA	3.145*** (5.43)	319	76/243	0.58
Sample C: ZAF, NGA, & unserved coastal countries excl.[a]	3.683*** (5.44)	250	66/184	0.61
Sample D: SSA excl. landlocked countries	3.665*** (5.57)	234	96/138	0.63
Controls	Ln GDP/cap, % 15- to 64-yrs-old pop, % of urban pop, % pop with electricity access, 2ndary educ index, democracy, area in km^2, landlockedness, IXP number			

t-student in parenthesis. $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. a: in sample C countries unserved by SMCs and excluded from the sample are the following: Benin, Comoros, Eritrea, Gambia, Guinea, Guinea-Bissau, Liberia, Mauritania, Madagascar, Sierra Leone, Somalia, and Togo.

4.2. Infrastructure deployment, digital vulnerability and the telecommunication sector development in SSA

The first round of OLS and fixed effect (FE) panel estimations in Tables 4 and 5 shows that infrastructure deployment variables are significant determinants of the telecommunication sector development. First, estimations in Table 4 show that including telecom infrastructure deployment variables strongly raises the explanatory power of regressions (columns (3) and (6)). Second, estimations highlight the positive and significant contribution of the deployment of SMCs and IXPs. Interestingly, estimated coefficients of the effect of SMC deployment on Internet penetration rates (Table 4, columns (3) and (6)) lie within the same range as previous DID estimates (resulting from samples B and C), thereby supporting the consistency of estimated relationships.

Third, estimations also point that SMCs had a more significant effect on final outcome variables than on intermediary outcome variables. In Table 5, FE estimations show that among intermediary telecom outcome variables, only telecom investment is significantly influenced, with the expected sign, by infrastructure deployment variables (column (6)): positively with the number of SMCs, and negatively with the number of SMC owners. In other words, SMC and IXP deployment is associated with higher investment in telecommunication and with a significant increase in Internet and mobile phone penetration, but unrelated to a change in communication tariffs or to greater telecommunication network stability.

Table 4. Infrastructure deployment and the telecom sector in SSA, OLS and *within* fixed-effect (FE) panel estimations (1/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
	OLS	FE	FE	OLS	FE	FE	OLS	FE	FE
Ln GDP/cap	0.461*	2.558	-0.333	1.459***	5.651*	0.204	5.334***	-0.504	-5.196
	(1.69)	(0.80)	(-0.14)	(4.52)	(1.88)	(0.09)	(5.91)	(-0.09)	(-1.09)
% of 15–24yrs	0.420***	1.131**	1.293**	0.508***	1.328***	1.545***	0.925***	3.053**	2.947**
	(3.90)	(2.18)	(2.60)	(5.78)	(3.16)	(4.10)	(2.95)	(2.63)	(2.56)
% urban pop	-0.050***	0.213	0.172	-0.099***	-0.723	-0.567*	0.129**	3.044**	2.704**
	(-3.78)	(0.65)	(0.60)	(-5.95)	(-1.63)	(-1.78)	(2.31)	(2.41)	(2.10)
Democracy	-0.171	-0.113	0.446	-0.342	-1.356	-0.592	-0.561	2.389	4.419
	(-0.76)	(-0.14)	(0.79)	(-1.43)	(-1.50)	(-0.81)	(-0.73)	(0.75)	(1.60)
2^{ary} Education	0.0179	-0.147	-0.142	-0.032*	-0.289**	-0.297***	0.107**	-0.777**	-0.818***
	(1.09)	(-1.26)	(-1.40)	(-1.88)	(-2.51)	(-3.03)	(2.06)	(-2.27)	(-2.96)
Electricity access (%)	0.062***	-0.0448	-0.132	0.059***	-0.0481	-0.0629	-0.00977	0.838	0.576
	(5.13)	(-0.30)	(-1.03)	(4.38)	(-0.49)	(-0.86)	(-0.23)	(1.35)	(1.04)
# IXPs			3.527***			2.462*			4.711
			(3.13)			(1.92)			(1.37)
# SMCs			3.450***			2.852***			-2.249
			(2.88)			(3.25)			(-0.70)
# years since 1st SMC			0.312*			0.440**			1.808***
			(1.77)			(2.10)			(3.33)
# SMC owners			-0.226**			-0.273*			0.165
			(-2.29)			(-1.91)			(0.45)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	778	778	778	418	418	418	818	815	818
# countries	46	46	46	44	44	44	46	46	46
R^2 (within)	0.539	0.533	0.665	0.609	0.563	0.685	0.770	0.819	0.847

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity.

Table 5. Infrastructure deployment and the telecom sector in SSA, OLS and *within* fixed-effect (FE) panel estimations (2/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
	OLS	FE	FE	OLS	FE	FE	OLS	FE	FE
Ln GDP/cap	-0.531***	-2.057	-1.902	0.172	-0.195	-0.553	-0.173*	-0.629	-0.648
	(-3.55)	(-1.25)	(-0.98)	(1.07)	(-0.23)	(-0.78)	(-1.74)	(-1.23)	(-1.24)
% of 15–24yrs	0.0279	0.393*	0.398*	-0.0571*	-0.0828*	-0.0596	-0.0024	-0.0944	-0.103^{+}
	(0.92)	(1.76)	(1.81)	(-1.94)	(-1.69)	(-1.04)	(-0.12)	(-1.36)	(-1.62)
% urban pop	0.00568	-0.231*	-0.231*	-0.021***	-0.0070	0.0223	-0.0005	0.0523	0.0675
	(0.78)	(-1.88)	(-1.92)	(-2.91)	(-0.12)	(0.57)	(-0.12)	(0.62)	(0.83)
Democracy	0.296**	0.214	0.182	0.220*	0.0475	0.0395	0.179**	0.0292	0.0580
	(2.29)	(0.96)	(0.83)	(1.79)	(0.21)	(0.19)	(2.04)	(0.12)	(0.22)
2^{ary} Education	0.0135*	0.0411	0.0343	0.0175**	-0.0043	0.00358	0.0061	-0.0011	-0.0008
	(1.79)	(1.64)	(1.33)	(2.36)	(-0.31)	(0.28)	(1.37)	(-0.07)	(-0.05)
Electricity	0.00817	-0.0223	-0.0182	0.00934	-0.0463*	-0.0482**	0.0010	-0.0422	-0.0423

access (%)	(1.43)	(-0.86)	(-0.73)	(1.27)	(-1.79)	(-2.17)	(0.26)	(-0.91)	(-0.97)
# IXPs			0.0143			0.112			-0.328
			(0.37)			(0.40)			(-1.29)
# SMCs			0.0577			0.953**			0.0461
			(0.15)			(2.24)			(0.18)
# years since 1st SMC			-0.229			-0.0536			0.0212
			(-0.70)			(-1.60)			(0.43)
# SMC owners			-0.0306			-0.0753**			-0.0123
			(-0.39)			(-2.08)			(-0.53)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	240	240	240	494	494	494	381	381	381
# countries	44	44	44	44	44	44	46	46	44
R^2 (within)	0.328	0.430	0.436	0.226	0.377	0.437	0.435	0.544	0.552

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity.

SMC exposure to seismic risk

The second round of estimations highlights the impact of the maritime infrastructure exposure to seismic risk, and is reported in Tables 6 and 7. The variable of annual frequency of seaquakes in the neighbourhood of SMC landing stations is computed according to three different radiuses: a 1000 km, a 500 km and a 100 km radius from SMC landing stations. The results show the negative impact of this source of digital vulnerability on telecom sector development, especially when the radius is set at 500 km from SMC landing stations. With this calibration, the exposure to seismic risk is found to negatively affect Internet penetration rates, mobile penetration rates and telecom investment, to have a positive and 5%-significant effect on mobile-cellular connection charges, and a positive 15%-significant effect on fixed-line phone faults. This last effect reaches a 5% significance level when the radius is extended to 1000 km from SMC landing stations, corroborating Carter et al.'s (2009) observation according to which, in 2006, almost one-third of cable breaks occurred in deep-sea water (probably more today, given the dramatic densification of the undersea cable network). Nonetheless, it is worth noting that the network instability variable is focused on the number of fixed phone line faults under the responsibility of public operators, and therefore does not take into account disturbances of the cellular network and those incurred on private operator networks (see the variable's definition in Online Appendix A). This variable therefore partially reflects, perhaps understates, the overall network instability, including the instability caused by seismic events.

Table 6. SMC exposure to seismic risk and the telecom sector development in SSA, *within* fixed-effect panel estimations (1/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
Seaquake freq 1000 km rad.	-0.129			-0.107			-0.315		
	(-1.23)			(-1.51)			(-0.53)		
Seaquake freq 500 km rad.		-0.272**			-0.116**			-1.349***	
		(-2.53)			(-2.45)			(-3.19)	
Seaquake freq 100 km rad.			-0.247**			-0.0959*			-1.149***
			(-2.36)			(-1.70)			(-2.97)
Controls	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	778	778	778	418	418	418	818	818	818
# countries	46	46	46	44	44	44	46	46	46
R^2 (within)	0.666	0.667	0.666	0.686	0.686	0.685	0.847	0.849	0.848

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Control estimates not reported in the table.

Table 7. SMC exposure to seismic risk and the telecom sector development in SSA, *within* fixed-effect panel estimations (2/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
Seaquake freq	-0.0445			0.0364			0.0833**		
1000 km rad.	(-0.69)			(0.61)			(2.05)		
Seaquake freq		0.295*			-0.170*			0.137	
500 km rad.		(1.71)			(-1.91)			(1.54)	
Seaquake freq			0.727***			-0.095			0.135
100 km rad.			(12.30)			(-1.24)			(1.07)
Controls	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	240	240	240	494	494	494	381	381	381
# countries	44	44	44	44	44	44	44	44	44
R^2 (within)	0.437	0.442	0.445	0.437	0.439	0.437	0.554	0.553	0.552

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Control estimates not reported in the table.

SMC outages

In a third step, having studied the seismic-induced risk of SMC outages, the analysis now turns to the actual experience of SMC outages. Tables 8 and 9 report the results when the shock variable of annual frequency of SMC outages is introduced in the regression equations. Estimates in columns (1), (4) and (7) in each table do not provide evidence of a significant impact of SMC outages on telecommunication outcomes. This lack of evidence could first be explained by differences in the resilience of the maritime infrastructure network to SMC outages, which in turn depends on available and functioning SMCs through which telecommunication traffic could be rerouted when cable breaks occur. A second explanation is the possible lagging effect of SMC outages on telecommunication outcomes.

First, to account for the resilience of the infrastructure network, equation (2) is augmented by adding an interaction term between the SMC outage variable and the number of SMC variables.[19] Estimates are reported in columns (2), (4) and (6) of Tables 8 and 9, and show that SMC outages have a negative impact on Internet penetration when controlling for the dampening effect of the number of SMCs (Table 8 column (2)). A higher number of SMC is also found to reduce the instability of the wireline telecommunication network following SMC outages (Table 9 column (8)).

Second, to account for the persistent lagging effect of SMC outages on telecommunication outcomes, one-year and two-year lags of this shock variable have been included in the regression. Estimates in Table 9 indicate a strong and significant negative effect of lagged SMC outages on Internet penetration among households and on mobile penetration rates. In particular, they show that one SMC outage in the past two years leads to a 2 percentage point decrease in the Internet penetration rate, and reduces by 10 the number of mobile subscriptions per 100 inhabitants. The mechanisms underlying these effects are not clearly identified (Table 9), but a possible explanation can be found in the lower utility for mobile and Internet users of having mobile phones and using Internet in a context of unstable telecommunication networks (Bjorkegren, 2018).

[19] By estimating:

$$TIC_{i,t} = \alpha_0 + \alpha_1.X_{i,t} + \alpha_2.INF1_{i,t} + \alpha_3.SMC\ outages_{i,t} + \alpha_4.[SMC\ outages \times SMC\ number]_{it} + \theta_i + \rho_t + \omega_{i,t}$$

Table 8. SMC outages, resilience and the telecom sector development in SSA, *within* fixed-effect panel estimations (1/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
SMC outages	0.490	-1.959*	0.708	-0.800	0.230	-0.771	-3.207	-5.065	-1.411
	(0.31)	(-1.91)	(0.42)	(-1.63)	(0.53)	(-1.41)	(-1.06)	(-1.50)	(-0.47)
SMC outages × # SMCs		1.872**			-0.751			1.414	
		(2.27)			(-1.34)			(0.69)	
SMC outages – Lag 1			0.091			-1.878**			-5.540
			(0.05)			(-2.57)			(-1.21)
SMC outages – Lag 2			-0.846			-2.231***			-10.536***
			(0.05)			(-2.74)			(-2.59)
Controls	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	778	778	778	418	418	418	818	818	818
# countries	46	46	46	44	44	44	46	46	46
R^2 (within)	0.665	0.671	0.665	0.686	0.689	0.695	0.847	0.848	0.849

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Control estimates not reported in the table.

Table 9. SMC outages and resilience of the telecom sector development in SSA, *within* fixed-effect panel estimations (2/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
SMC outages	-0.0044	-0.306	-0.105	-0.003	0.421	-0.037	-0.654	0.208	-0.674
	(-0.02)	(-1.46)	(-0.34)	(-0.01)	(1.29)	(-0.14)	(-1.41)	(0.38)	(-1.34)
SMC outages × # SMCs		0.163			-0.277			-0.465**	
		(1.06)			(-1.38)			(-2.52)	
SMC outages – Lag 1			-0.130			-0.017			-0.471
			(-0.35)			(-0.06)			(-0.94)
SMC outages – Lag 2			0.090			0.120			-0.373
			(0.17)			(0.32)			(-1.17)
Controls	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}	X_{it}, SMC_{it}
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	240	240	240	494	494	494	381	381	381
# countries	44	44	44	44	44	44	44	44	44
R^2 (within)	0.436	0.437	0.436	0.437	0.440	0.437	0.556	0.560	0.558

t-student in parenthesis* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Control estimates not reported in the table.

Digital isolation

In a fourth step, the contribution of digital isolation variables is studied. Tables 10 and 11 highlight the contribution of digital isolation, approximated by three distance variables: the demographic distance, the geographic distance and the capital distance to SMC landing stations. Compared to previous estimations, including digital isolation variables in the regressions using Internet penetration rates (Table 10, columns(1) to (6)) and the number of faults per 100 fixed lines (Table 11, columns (7) to (9)) as dependent variables leads to a strong increase in their explanatory power. Among digital isolation variables, demographic distance appears to be the most significant and most relevant proxy, but geographic distance is found to have a stronger effect on Internet penetration in the population (Table 10, column (2)), on telecommunication tariffs (Table 11, column (2)) and on the number of fixed line faults (Table 11, column (8)). Demographic distance is however found to significantly reduce the number of mobile subscriptions per 100 inhabitants, which geographic distance does not. Moreover, all digital isolation proxies are found to significantly contribute to the telecommunication network instability. Therefore, this collection of evidence suggests that digital isolation is an important source of a country's digital divide, and a critical dimension of a country's digital vulnerability.

Table 10. Digital isolation and ICT development in SSA, *within* fixed-effect panel estimations (1/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	% pop using the Internet			**% HH with Internet**			**# of mobile subscript / 100 inhab.**		
Ln demo distance	-0.794** (-2.05)			1.110 (1.39)			-3.115** (-2.08)		
Ln geo distance		-0.854** (-2.05)			0.822 (0.75)			-2.548 (-1.43)	
Ln capital distance			0.313 (1.34)			0.348 (1.60)			-0.271 (-0.39)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	703	702	699	381	381	382	735	734	731
# countries	44	44	46	44	44	44	44	44	46
R^2 (within)	0.735	0.735	0.708	0.736	0.733	0.743	0.864	0.863	0.872

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Control estimates not reported in the table.

Table 11. Digital isolation and ICT development in SSA, *within* fixed-effect panel estimations (2/2)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Prepaid mobile cell connect charge			**Telecom investment**			**# of fixed line faults**		
Ln demo distance	0.594** (2.49)			0.032 (0.28)			0.365*** (4.30)		
Ln geo distance		0.816*** (3.05)			0.082 (0.68)			0.383*** (3.71)	
Ln capital distance			0.060 (0.50)			-0.081 (-1.40)			0.0884* (1.71)
Controls	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$	X_{it}, $INF1_{it}$
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	215	214	218	432	431	433	323	323	334
# countries	42	41	42	41	40	41	42	42	42
R^2 (within)	0.438	0.446	0.446	0.456	0.457	0.457	0.603	0.602	0.592

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. Control estimates not reported in the table.

5. Concluding remarks

This paper opens new perspectives for the economic literature on the benefits and risks of the increasing digitalization of economies, especially developing economies. It provides new insights into the telecom infrastructure's contribution to the telecom sector in SSA, but also underlines the vulnerability of SSA to failures in its telecommunication network. In fact, while the deployment of SMC has on average strongly stimulated the ICT sector in SSA, this sector's development is still exposed to SMC outages and hampered by the digital isolation of countries and populations remote from SMC landing stations.

In a first step, a diff-in-diff approach was followed to study the impact of SMC waves that landed in SSA on the development of the ICT sector. Among these different waves, the impact of the 2009 SEACOM and the 2010 MainOne and EASSy waves could be studied within the DID estimation framework. Results stress that their arrival is associated with a 6 percentage point increase in Internet penetration rates, mostly driven by South Africa and Nigeria. Once these two countries have been excluded from the sample, this impact remains 1%-significant but falls to 3 percentage points. Moreover, excluding landlocked countries does not affect the strength and significance of coefficients, thereby suggesting that the arrival of SMCs has been beneficial to both coastal and landlocked countries, probably by reducing the latter's digital isolation.

The issue of digital vulnerability related to the deployment of SMCs is then studied within a panel fixed-effect estimation framework. First, results indicate that taking digital vulnerability variables, especially digital isolation, into consideration strongly increases the explanatory power of regressions. Second, digital isolation, proxied by the demographic-centroid distance to SMC landing stations, has a negative and significant impact on Internet and mobile penetration rates, and a positive and significant impact on mobile subscription charges and on the annual number of faults per 100 fixed lines. Third, the role of the infrastructure exposure to seismic activity is also found to be significant, as the annual frequency of seaquakes in the neighbourhood of SMCs has a negative impact on Internet and mobile penetration rates and on telecom investment, and a positive impact on mobile subscription charges and network instability. Fourth, estimations also point to the negative and lasting impact of SMC outages on Internet penetration rates, especially in countries relying on just a few SMCs. This last result therefore indicates that hosting a large number of SMCs not only increases Internet traffic, speed and capacity, but also lowers the countries' vulnerability to cable outage and therefore increases the telecom network's resilience.

All in all, this paper is in some way related to Malecki's (2002, p.399) view on the geography of the Internet infrastructure, in stressing that "interconnection is both critical to the functioning of the Internet and the source of its greatest complications".

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Appendices

A. Variable sources, definition and descriptive statistics.

A.1. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max	Obs.	Countries
% pop using Internet	3.599857	6.634304	0	47.076	778	46
% HH with fixed Internet	3.090524	5.706059	0	41.92	412	44
Ln # mobile subscript	20.88281	29.6036	0	179.4714	773	46
Ln mobile-cell prepaid subscript charge	2.267642	1.357488	0	9.720285	235	44
Ln telecom invest	17.45	1.9881	11.3262	27.06795	462	44
Fixed line faults	3.479371	1.341012	0.0295588	7.06732	351	44
Ln GDP/cap	6.592359	1.098209	4.62277	9.53892	778	46
% of 15–24yrs	54.16216	4.352466	47.40301	71.45077	778	46
% urban pop	37.24095	16.49959	7.211	86.4576	778	46
Democracy status	2.105398	0.7187123	1	3	778	46
2^{ary} Education index	28.79894	23.35361	0	100	778	46
Electricity access (%)	34.34615	24.96251	0.5558459	100	778	46
# SMCs	0.3881748	0.8510507	0	6	778	46
# IXPs	0.2172237	0.5372713	0	6	778	46
# SMC owners	4.46144	8.961475	0	59	778	46
# years since 1st SMC*	-1.661954	5.836037	-17	18	778	46
Ln demographic distance	6.627677	1.353204	0	8.558235	703	45
Ln geo distance	6.7562	1.208164	0	8.566905	702	44
Ln capital distance	5.912122	2.573306	0	8.557826	699	46
Seaquake freq 500 km rad.	0.0989717	0.9662111	0	25	778	46
Seaquake freq 100 km rad.	0.0488432	0.8744507	0	24	778	46
Seaquake freq 1000 km rad.	0.3791774	1.546842	0	28	778	46
SMC outages	0.0257069	0.1583614	0	1	778	46

* This variable is forward looking, so negative values mean the country is *t* year(s) before SMC arrival.

A.2. Sample composition

Country Code	Freq. obs	Per cent	Country Code	Freq. obs	Per cent
AGO	17	2.19	MDG	17	2.19
BDI	18	2.31	MLI	17	2.19
BEN	17	2.19	MOZ	17	2.19
BFA	17	2.19	MRT	16	2.06
BWA	18	2.31	MUS	17	2.19
CAF	17	2.19	MWI	16	2.06
CIV	18	2.31	NAM	18	2.31
CMR	16	2.06	NER	17	2.19
COG	17	2.19	NGA	17	2.19
COM	16	2.06	RWA	16	2.06

CPV	16	2.06	SDN	15	1.93
DJI	18	2.31	SEN	18	2.31
ERI	14	1.8	SLE	18	2.31
ETH	18	2.31	STP	13	1.67
GAB	17	2.19	SWZ	18	2.31
GHA	18	2.31	SYC	16	2.06
GIN	18	2.31	TCD	16	2.06
GMB	18	2.31	TGO	18	2.31
GNB	16	2.06	TZA	17	2.19
GNQ	16	2.06	UGA	18	2.31
KEN	18	2.31	ZAF	18	2.31
LBR	14	1.8	ZMB	18	2.31
LSO	17	2.19	ZWE	18	2.31
			Total	**778**	**100**

A.3. Pairwise cross-correlations (1/2)

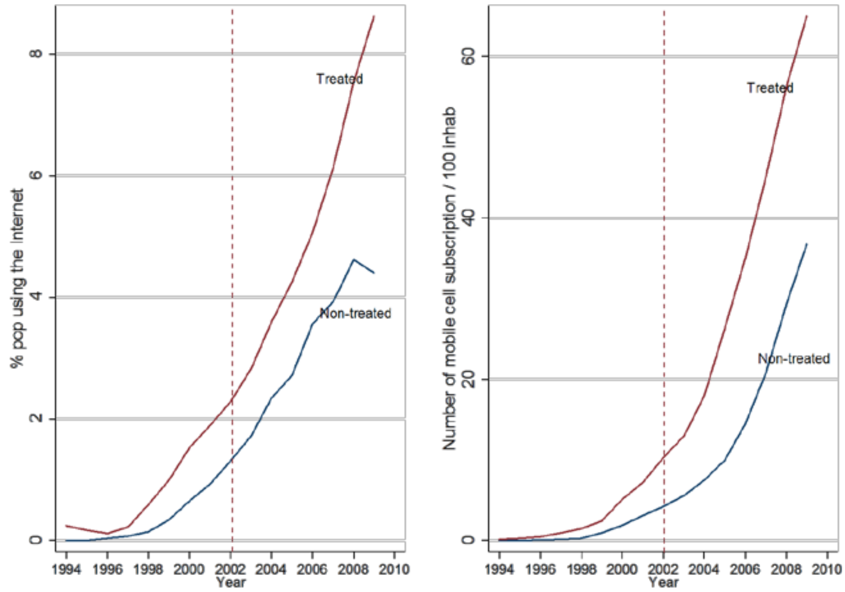
	% pop using Internet	% HH with fixed Internet	Ln # mobile subscript	Cell repaid connect charge	Fixed line faults	Ln telecom invest	# SMCs	# IXPs	# SMC owners	# years since 1st SMC	Seaquake freq 1000 km rad.
% pop using Internet	1										
% HH with fixed Internet	0.8409*	1									
Ln # mobile subscript	0.7163*	0.6520*	1								
Cell prepaid connect charge	-0.2746*	-0.1950*	-0.4604*	1							
Fixed line faults	-0.3970*	-0.1955	-0.5429*	0.2543*	1						
Ln telecom invest	0.3287*	0.3254*	0.3927*	-0.1839	-0.3058*	1					
# SMCs	0.5194*	0.4533*	0.4506*	-0.0831	-0.4043*	0.4208*	1				
# IXPs	0.4445*	0.3406*	0.3461*	-0.2807*	-0.1971*	0.4539*	0.4562*	1			
# SMC owners	0.4500*	0.3445*	0.4514*	-0.0521	-0.4160*	0.3589*	0.9341*	0.4028*	1		
# years since 1st SMC	0.3977*	0.3733*	0.4295*	-0.1075	-0.3958*	0.3333*	0.6370*	0.2763*	0.6614*	1	
Seaquake freq 1000 km	0.0279	0.1624*	0.0014	0.0399	0.0541	-0.11	0.1198*	-0.0266	0.1084*	0.0397	1
Seaquake freq 500 km	-0.0252	-0.0125	-0.0388	0.1254	-0.0043	-0.1605*	0.1194*	-0.0348	0.1050*	0.0761	0.7874*
Seaquake freq 100 km	0.0019	-0.0108	-0.0058	0.1116	0.0595	-0.1168*	0.1407*	-0.019	0.1240*	0.1150*	0.4669*
SMC outages	0.0769	-0.0337	0.1361*	-0.0856	-0.1506*	0.1328*	0.1409*	0.1063*	0.1131*	0.1063*	-0.0045
Ln geo distance	-0.4575*	-0.4675*	-0.4752*	-0.0177	0.3649*	-0.1129	-0.4574*	-0.0588	-0.4707*	-0.4579*	-0.2041*
Ln capital distance	-0.3503*	-0.2544*	-0.4481*	-0.006	0.4530*	-0.067	-0.5913*	-0.0781	-0.6740*	-0.5579*	-0.1503*
Ln demographic distance	-0.4521*	-0.4219*	-0.4804*	-0.0331	0.3765*	-0.0998	-0.5182*	-0.0601	-0.5449*	-0.5126*	-0.2056*
Ln GDP/cap	0.4540*	0.5233*	0.4591*	-0.0876	-0.1601*	0.1775*	0.2402*	0.1798*	0.2717*	0.1129*	0.0436
% of 15–24yrs	0.5783*	0.6465*	0.5112*	-0.026	-0.2349*	0.1668*	0.2837*	0.2392*	0.2837*	0.1447*	0.1417*
% urban pop	0.2861*	0.2039*	0.3779*	-0.0006	-0.1265	0.0041	0.3832*	0.0588	0.4515*	0.1526*	0.1217*
Democracy status	-0.2165*	-0.1946*	-0.1658*	0.0365	0.1453*	0.008	-0.1141*	-0.1451*	-0.1613*	-0.1500*	0.0545
2^{ary} Education index	0.5811*	0.5635*	0.5648*	-0.1311	-0.3003*	0.2720*	0.3152*	0.3442*	0.3289*	0.1910*	-0.0107
Electricity access (%)	0.5028*	0.5082*	0.4637*	0.0539	-0.2130*	0.1621*	0.3504*	0.1612*	0.4038*	0.2419*	0.0892*
Being landlocked	-0.1265*	-0.1615*	-0.1176*	-0.1182	0.0779	-0.1262*	-0.3166*	0.0227	-0.3389*	0.1167*	-0.1792*
Area, in km^2	0.1105*	0.2520*	0.0265	-0.0606	0.0004	0.4048*	0.1414*	0.1849*	0.0375	0.0646	-0.0904

A.3. Pairwise cross-correlations (2/2)

	Seaquake freq 500 km	Seaquake freq 100 km	SMC outages	Ln geo distance	Capital distance	Demographic distance	GDP/cap	% of 15–24yrs	% urban pop	Democracy status	2^{ary} Educ index	Electricity access (%)	Landlocked
Seaquake freq 500 km	1												
Seaquake freq 100 km	0.6271*	1											
SMC outages	-0.0017	0.0111	1										
Ln geo distance	-0.1007*	-0.0943*	-0.0481	1									
Ln capital distance	-0.1207*	-0.0848	-0.062	0.7519*	1								
Ln demographic dist.	-0.1228*	-0.1254*	-0.0562	0.9816*	0.8041*	1							
Ln GDP/cap	0.0197	0.0136	-0.0558	-0.2483*	-0.2815*	-0.2616*	1						
% of 15–24yrs	0.0053	0.0818	-0.0294	-0.4275*	-0.2974*	-0.4256*	0.6738*	1					
% urban pop	0.0899*	0.1190*	-0.0262	-0.2964*	-0.4589*	-0.3753*	0.6125*	0.4545*	1				
Democracy status	0.1017*	0.0427	-0.0417	0.0503	0.1541*	0.0697	-0.2056*	-0.3592*	-0.1848*	1			
2^{ary} Education index	-0.0761	-0.0078	0.0101	-0.3489*	-0.2900*	-0.3379*	0.6992*	0.7860*	0.4788*	-0.4298*	1		
Electricity access (%)	0.0348	0.0348	-0.0321	-0.5109*	-0.4719*	-0.5235*	0.7814*	0.7163*	0.6426*	-0.2729*	0.6976*	1	
Being landlocked	-0.0873*	-0.0355	-0.0082	0.3190*	0.3849*	0.3337*	-0.2161*	-0.2859*	-0.4778*	0.0406	-0.2327*	-0.4841*	1
Area, in km^2	-0.0247	-0.0471	0.0105	0.1950*	0.1086*	0.1751*	0.0778	-0.0713	-0.0506	-0.0018	-0.017	-0.0735	-0.041

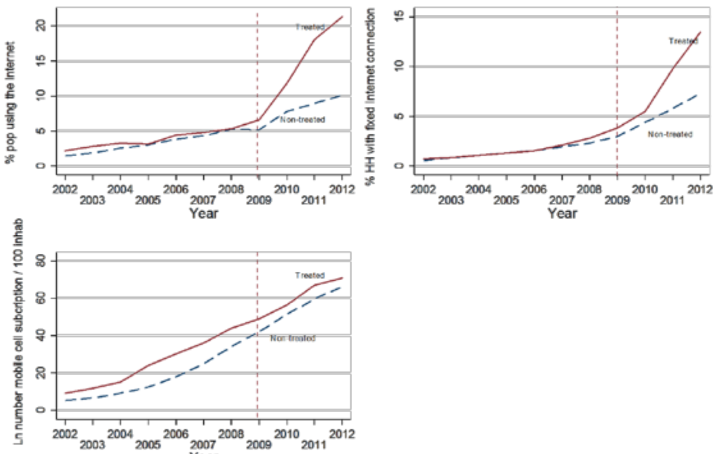
B. Diff-in-diff analysis: other regional waves of SMCs

B.1. SAT3/SAFE (2002)

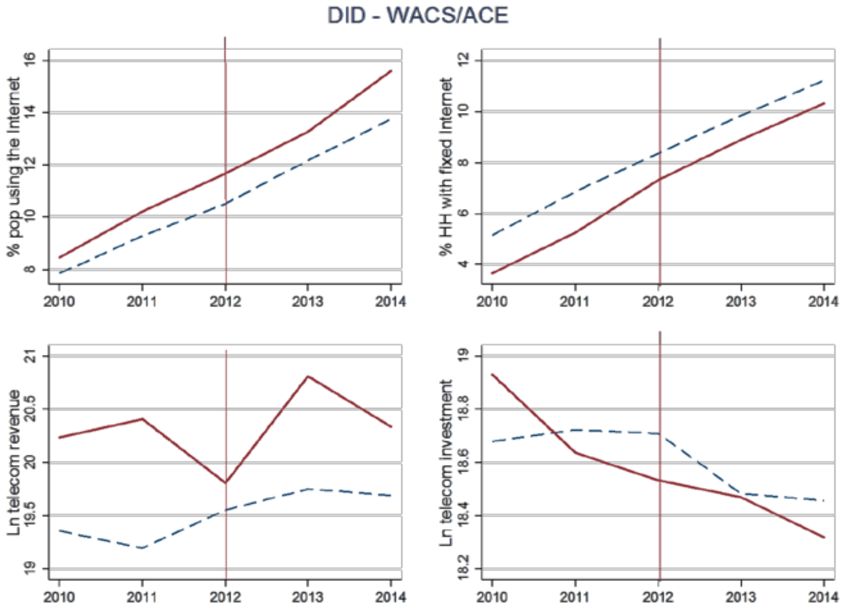


Note: Because of missing data, the evolution of other ICT variables in treated and non-treated groups is not reported.

B.2. SEACOM (2009)



B.3. WACS/ACE (2012)



Note: Because of missing data, the evolution of the share of households with the fixed Internet connection variable and of the fixed phone line faults variable in treated and non-treated groups is not reported.

ONLINE APPENDIX

A. Variable sources and definitions

Variable	**Source**	**Definition**
% pop using Internet	ITU	Percentage of individuals using the Internet
% HH with Internet	ITU	Percentage of households with Internet connection
Ln # mobile subscript	ITU/World Bank	Mobile cellular telephone subscriptions are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology. The indicator includes (and is split into) the number of post-paid subscriptions, and the number of active prepaid accounts (i.e. that have been used during the last three months). The indicator applies to all mobile cellular subscriptions that offer voice communications. It excludes subscriptions via data cards or USB modems, subscriptions to public mobile data services, private trunked mobile radio, telepoint, radio paging and telemetry services.
Ln mobile-cell prepaid connection charge	ITU	The initial, one-time charge for a new subscription. Refundable deposits should not be counted. Although some operators waive the connection charge, this does not include the cost of the Subscriber Identity Module (SIM) card. The price of the SIM card should be included in the connection charge (for a prepaid service the cost of SIM is equivalent to the connection charge). It should also be noted whether free minutes or free SMSs are included in the connection charge. Taxes should be included. If not included, it should be specified in a note including the tax rate applicable.
Ln telecom invest	ITU	
Fixed line faults	ITU	The total number of reported faults to fixed telephone lines for the year. Faults that are not the direct responsibility of the public telecommunications operator should be excluded. This is calculated by dividing the total number of reported telephone faults for the year by the total number of fixed lines in operation and multiplied by 100. The number of faults per 100 fixed lines per year should reflect the total reported by all PSTN service providers in the

		country.
Ln GDP/cap	World Bank	GDP per capita in 2005 constant USD
% of 15–24yrs	World Bank	Population ages 15–64 (% of total)
% urban pop	World Bank	Urban population (% of total)
Democracy status	Freedom House	1=not free ; 2=partly free; 3=free
2^{ary} Education index	Ferdi/UNDP	Gross secondary school enrolment ratio. According to the UNDP, this indicator measures the number of pupils enrolled in secondary schools, regardless of age, expressed as a percentage of the population in the theoretical age group for the same level of education. Missing raw data have been filled through linear interpolation and extrapolation, and transformed into an index between 0 and 1 by a minmax procedure (Feindouno & Goujon, 2016).
Electricity access (%)	World bank	Percentage of population with access to electricity. Electrification data are collected from industry, national surveys and international sources. Missing data have been inter- and extrapolated using five-year moving average.
# SMCs	Author, Telegeography	Number of submarine cables laid in a given country
# IXPs	Author Telegeography, Author, Packet Clearing House and Peering DB	Number of Internet exchange points built in a given country
# SMC owners	Author, Telegeography	Summation of SMC owners associated with cables laid in a given country
# years since 1st SMC*	Author, Telegeography	Number of years passed since first fibre-optic SMC arrival. This variable is forward looking, so negative values mean the country is *t* year(s) before SMC arrival.
Ln geo distance	Author, Telegeography	The geographic distance is the country's centroid distance to the closest SMC landing station. When countries have no SMCs (such as landlocked countries), the distance to the closest neighbour's SMC landing station is taken.
Ln demographic distance	Author, Telegeography	The demographic distance is the country's centroid distance, weighted by the spatial distribution of the population, to the closest SMC landing station. When countries have no SMCs (such as landlocked countries), the demographic distance to the closest neighbour's SMC landing station is taken.

Ln capital distance	Author, Telegeography	The capital distance is the country's capital distance to the closest SMC landing station. When political capital differs from economic capital, the economic capital is taken as reference. When countries have no SMCs (such as landlocked countries), the distance to the closest neighbour's SMC landing station is taken.
Seaquake freq 500 km	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquakes above 5 on the Richter scale within a 500 km radius from a country's SMC landing station
Seaquake freq 100 km	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquakes above 5 on the Richter scale within a 1000 km radius from a country's SMC landing station
Seaquake freq 1000 km	Author, Telegeography, Northern California Earthquake Data Center	Annual number of seaquakes above 5 on the Richter scale within a 100 km radius from a country's SMC landing station
SMC outages	Author	Annual number of SMC outages reported on the Web.

B. ICT infrastructure data collection and treatment

B.1. Infrastructure deployment variables

Raw data on SMCs are drawn from Telegeography:

- All cables with date of commissioning
- All the landing stations of cables and their GPS coordinates
- The number and identity of telecoms operator owners of cables

Raw data on Internet exchange points are drawn from Telegeography and completed by the *Packet Clearing House* and *Peering DB* databases:

- All IXPs with their status (active/inactive/project)
- their year of activation
- their GPS coordinates

After a conversion into polygons (disk with 5 km diameter) to avoid topological inaccuracies, the SMC landing points and IXPs from each country are identified, located and counted. Then, for each country, all cables related to these points and all IXPs are identified, which gives **the number of cables** and **the number of IXP** variables.

The number of years since the first cable arrival is obtained by calculating the difference between the current year and the year of the first SMC's activation for each country. This variable is forward looking and can take negative values at time t when the activation year occurs at time t + k.

Using information from Telegeography on the SMC ownership structure, **the number of cable owners** is calculated for each country by summing the number of cable owners associated with all SMCs laid in that country.

B.2. Digital isolation proxies

Statistical inputs: SMC landing station coordinates, countries' centroids, spatial distribution of the population.

a. Country with cables: From the SMC landing points of a given country, the distance to each point of its territory is calculated in the form of a raster map with the Spatial Analyst's Cost Distance tool, using the Winkel III projection. The Zonal Statistics tool then gives us the distance from the centroid of the country to the closest SMC landing station.

b. Country without cables: From the closest foreign SMC landing points, the distance to each terrestrial point of the world is calculated as previously.

B.3. Exposure to seaquake-induced cable faults

The Northern California Earthquake Data Center of the University of California, Berkeley, provides a global database of earthquakes. For each country, we get for each year the number, the location and the average magnitude of epicentres of occurring seaquakes and are therefore able to compute the annual frequency of seaquakes within 1000/500/100 km radiuses of the stations. To ensure that we do take into account seaquakes that are strong enough to induce cable faults, we only count seaquakes with magnitudes exceeding 5 on the Richter scale. Therefore, seaquakes considered for the empirical analysis are those occurring within a 1000 km radius from SMC landing stations.

B.4. SMC outages in SSA, web-based event study.

SMC	**Year**	**Countries or region affected**	**Fault duration**
EASSy	2017	Somalia	3 weeks
WACS	2017	Congo Rep.	15 days
MainOne	2017	West Africa, Cameroon	14 days
SEACOM	2016	East & South Africa	.
SAT-3	2015	Gabon	4 days
SAT-3	2015	Gabon	2–3 days
SAT 3	2015	Nigeria	-
unknown	2012	Nigeria	-
TEAMS et EASSY	2012	Kenya, Burundi, Rwanda & Tanzania	15 days
SAT-3	2011	Benin, Niger, Togo, & Burkina-	10–15 days

		Faso	
SEACOM	2010	East Africa, Europe (France & GB), India	8 days
SAT-3	2010	Benin, Niger, Togo & Nigeria	3 weeks
SEA-ME-WE 3, SEA-ME-WE 4 & FLAG FEA	2008	Saudi Arabia, Djibouti, Egypt, UAE, India, Lebanon, Malaysia, Pakistan, Qatar, Syria, Taiwan, Yemen, Zambia, Malta & Italy	12 days

C. DID in Internet penetration rates, before and after wave 2 (SEACOM)

	DID parameters (δ_3)	**# observations**	**# treated/control obs**	**R-squared**
	Period 2002–2012			
	% population using the Internet			
Sample A: SSA	4.526*** (3.90)	441	44/397	0.59
Sample B: SSA excl. ZAF and NGA	3.145*** (2.78)	419	33/386	0.51
Sample C: ZAF, NGA, & unserved coastal countries excl.	2.990** (2.45)	344	33/311	0.51
Sample D: SSA excl. landlocked countries	4.503*** (3.40)	288	44/244	0.59
	% HH with Internet connection			
Sample A: SSA	2.694*** (3.31)	371	44/327	0.57
Sample B: SSA excl. ZAF and NGA	0.50 (0.38)	349	33/316	0.50
Sample C[a]: ZAF, NGA, & unserved coastal countries excl.	0.357 (0.42)	297	33/264	0.54
Sample D: SSA excl. landlocked countries	2.414** (2.51)	254	44/210	0.57
	Period 1990–2014			
	% population using the Internet			
Sample A: SSA	4.508*** (5.22)	760	79/681	0.60
Sample B: SSA excl. ZAF and NGA	2.874*** (3.43)	719	56/663	0.55
Sample C[a]: ZAF, NGA, & unserved coastal countries excl.	2.654*** (2.97)	589	56/533	0.56
Sample D: SSA excl. landlocked countries	4.486*** (4.48)	498	79/419	0.59
	% HH with Internet connection			

Sample A: SSA	2.698*** (3.32)	373	44/329	0.57
Sample B: SSA excl. ZAF and NGA	0.314 (0.38)	351	33/318	0.50
Sample C[a]: ZAF, NGA, & unserved coastal countries excl.	0.364 (0.43)	299	33/266	0.54
Sample D: SSA excl. landlocked countries	2.426** (2.53)	256	44/212	0.57
Controls	Ln GDP/cap, % 15-64 yrs-old pop, % of urban pop, % pop with electricity access, 2ndary educ index, Democracy, area in km2, landlockedness, IXP number			

t-student in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to heteroscedasticity. a: in sample C countries unserved by SMCs and excluded from the sample are the following: Benin, Comoros, Eritrea, Gambia, Guinea, Guinea-Bissau, Liberia, Mauritania, Madagascar, Sierra Leone, Somalia, and Togo.