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The measurement of internet availability and quality in the context of the discussion on digital divide

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**Zentrum für internationale Entwicklungs- und Umweltforschung der
Justus-Liebig-Universität Gießen**

**The Measurement of Internet Availability and Quality in
the Context of the Discussion on Digital Divide**

by

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No. 65

Gießen, September 2015

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v2.0

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Latency

Abstract

My contribution is concerned with measures of Internet quality and availability used and usable in the analysis of the so called *digital divide*. The usage of the share of Internet users in the population – widely used in economic analysis – can easily be misleading in this debate, suggesting that the digital divide is narrowing. This appears to be an artifact of the data, as some industrialized countries are already close to a share of 100 % Internet users in the population, while the ratio of Internet users to total populations is still growing for developing countries.

I argue that one should focus on the study of Internet quality provided in a demand and supply model of infrastructure. To this end, I introduce a new latency-based measure to judge the quality of Internet, based on a novel data set, and compare it to related measures. The results indicate that it may indeed be useful to measure Internet quality across countries. In particular the availability of the indicator for 247 countries and semi-autonomous regions makes it an interesting tool for policy analysis.

The possibility to examine the effects of different determinants on individual quantiles is particularly interesting. ICT investment appears to be strongly correlated with lower latency (better Internet quality) in the lower part of the distribution, while there appears to be little explained variation in the top of the latency distribution. In addition we find that population density is an important determinant of latency – an argument which is brought up in the theoretical discussion on ICT investment but – to my knowledge – not found empirically to date.

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1. Introduction

The Internet is an infinite source of knowledge and an important tool of communication. It constitutes a potential input for economic development, as ideas spread easily and transaction costs in many fields are drastically reduced. Therefore, one could suspect that differences in availability and usage of Internet lead to differences in economic outcomes. This phenomenon, dubbed the “digital divide”, provoked a fair amount of research in economics and related sciences. The studies of the consequences are related to the relationship between Information and Communication Technology (ICT) use and growth (Dasgupta et al., 2001), inequality (DiMaggio and Hargittai, 2001), and political participation (Sylvester and McGlynn, 2010) on the one hand. On the other hand, there are important firm specific questions about the impact of ICT usage on productivity and innovation (Bertschek et al., 2013).

To mitigate the potential adverse effects of the digital divide the study of its determinants is important. One widely used approach is the study of Internet diffusion, which is based on the share of population in a country that uses the Internet *at all*. This measure has some weaknesses, as it disregards any information on connection quality, way of access and utilization of Internet.

Based on this measure one could get the idea that developing countries are somehow catching up as suggested by Cuberes et al. (2010). Internet usage, measured in terms of the share of the population using the Internet, is approaching the upper bound of 100% in industrialized countries and Internet usage in developing countries is still increasing (Indicated by the shift from t' to t'' in Figure 1). While the interpretation that the digital divide is narrowing might be a measurement artifact due to the ratio of Internet users in the population approaching the upper bound, it neglects important aspects of Internet access quality in terms of speed (Latency and Bandwidth), as well as reliability and availability. This is particularly troublesome as connections in developing countries tend to be unstable and the availability of access is often limited to a few international hotels and universities. When measuring the share of Internet users, the indicator does not reflect whether the users have occasional or regular Internet access.

The aim of this paper is twofold: In a first step I address the question how the digital divide should be measured. For that purpose I discuss the suitability of latency as a measure of Internet quality and how it compares to the penetration rate and international bandwidth. For that purpose I introduce a novel dataset constructed from Carna Botnet (2013). In the second step I analyze

Figure 1: S-Shape of technological diffusion

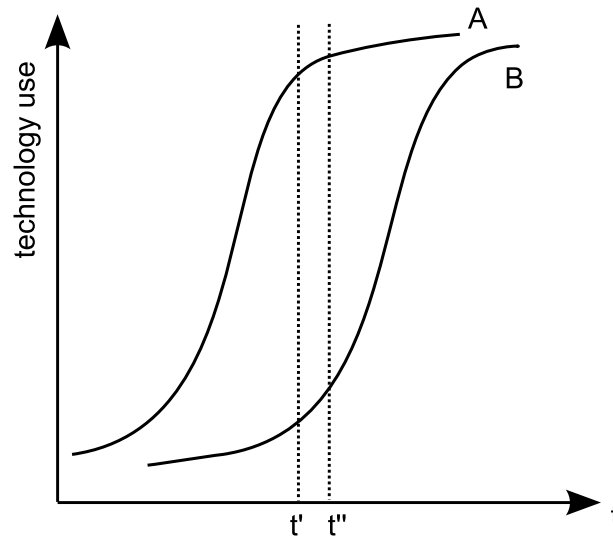


Illustration of the process of Internet diffusion in an industrialized country (A) and a developing country (B)

the determinants of Internet provision and point out how these determinants differ across different indicators.

The remainder of this paper is structured as follows: Section 2 summarizes the debate on Internet diffusion and discusses different measures of Internet usage and quality in their applicability in this context. Section 2.2 in particular explains the technological and conceptual background of *latency* in relationship to (computer) networks. Moreover, I try to disentangle the two related terms of latency and bandwidth when it comes to Internet speed. Section 2.3 describes the nature of the data and the process of aggregation and closes with some descriptive results on the distribution of latency times across countries. Finally, in Section 3 I set up a simple model of demand and supply and estimate it for different measures of Internet quality and usage using three stage least squares (3SLS).

2. The Study of Internet diffusion

Research in the field of digital divide, is strongly connected with the theory of technological diffusion. The epidemic models around which the theory of technology diffusion is based are dating back to Griliches (1957). The basic idea of these models is that exposure to a new invention in a neighboring region will lead to the adoption of the technology in the home region. The usage of the new technology grows exponentially at first and is later only slowly adopted by the more conservative producers, which leads to the famous S-shape depicted in Figure 1.

Research in this direction includes Chinn and Fairlie (2010), who apply Blinder-Oaxaca decomposition on data on Internet adoption and computer ownership, finding that income differences are the main source of the digital divide. Unfortunately, many of their explanatory variables are correlated with GDP and there are potential issues of endogeneity (e.g. the inclusion of electric power consumption).

Other authors try to explain Internet penetration by introducing different socio-economic explanatory variables. Cuberes et al. (2010) test for network effects through the inclusion of lagged values of Internet usage. They try to address the resulting endogeneity concern by using an Aranello-Bond estimator. They claim to have found evidence of network effects, through the significant predictive power of the lagged number of Internet users. Wunnava and Leiter (2008) try to explain Internet penetration through income inequality (measured by a Gini-coefficient) in addition to the standard explanatory variables like telecommunication infrastructure, constructed from telephone and computer penetration.

However, in the context of epidemic models technologies are related to narrow applications (see Griliches's initial application to a new kind of hybrid corn). In contrast the Internet is very universal in its scope and just sets out a foundation for other technologies to be used on top, and requires substantial investment in infrastructure to yield any returns. The applications build on-top of the infrastructure including simple technologies like Internet-based time synchronization (via ntp - network time protocol) as well as recent inventions in the areas of telemedicine and video conference systems.

The availability and the limits to the utilization of Internet, depend to a large extent on governments and telecommunication providers. The situation is in many cases similar to road infrastructure: I can connect my front door to the road, which is in most cases financed by the government. Nonetheless, whether my shoes get dirty on the way to work depends more heavily on whether there the municipal road is paved, rather than on my own investment in the three meters between pavement and doorstep.

Therefore, I would argue that epidemic models do not very well reflect the provision of Internet infrastructure (primarily fiber-optic cables). The process is better reflected by supply and demand of infrastructure, similarly to Röllner and Waverman (2001) who model the impact of phones on economic development.

2.1. The Different Facets of the "Digital Divide"

The choice of *measure* of the "Digital Divide" is of great importance. Using the number of users as a proxy for Internet infrastructure, is problematic. It omits any measure of quality but includes users regardless of their mean of access. The latter could be important as countries are very heterogeneous in terms of the composition of technologies used to access the Internet. Dial-up connections are used in areas where fixed-line phones are common. Wireless technology is - at least for telecommunication - very common in developing countries. Each technology has its own advantages in terms of availability and reliability on the one hand, and bandwidth and latency on the other hand. Moreover, the focus on users rather than hardware is likely to result in an underestimation of the digital divide, as private possession of computers is more pronounced in industrialized countries. The mean of access differs as well across countries. In industrialized countries, every user tends to have his or her own computer or Internet capable device, as well as their own broadband connection. In developing countries most users can only gain Internet access from libraries, universities, Internet cafes or at the workplace rather than at home.

Having or not-having an uplink does not fully reflect the access to information either. In the absence of net neutrality the flow of information may even be artificially constrained. There is anecdotal evidence (Mirani, 2015) that there are more Facebook users than Internet users in developing countries, because Facebook is offering subsidized data plans which only allow the Facebook-App to access the Internet while its data plans prohibit the use of the free Internet.

Measuring the IT dispersion in terms of hosts or servers would result in even larger gaps - as the majority share of infrastructure is hosted in the United States and Western Europe, while its users, administrators and owners might be spread all over the world. Despite these potential limitations the measure of the number of hosts is used in the literature. The number of hosts (Kiiski and Pohjola (2002), Hargittai (1999)) and the number of IP addresses (Miner (2012)) are, in this discussion, two sides of the same coin. IP address have the additional drawback that IP address space was allocated freely in the early phase of Internet development and is scarce today. As a consequence Hewlett-Packard, one of the early large American IT companies still holds more IPs¹ than Spain (28 million public addresses²). Depending on the actual measurement technique this might also bias the

¹ HP initially was allocated a block of 16 million IPs and received an additional block of the same size with the acquisition of Compaq.

² According to <http://www.nirsoft.net/countryip/es.html>, accessed January 2014.

number of hosts. In some environments every printer might have a public IP and show up as a host, reachable from the outside. While in cases where IPs are scarce people increasingly use *network address translation*, where several computers or even households and institutions only receive one single public IPv4 address.³ This critique might be more relevant in a comparison across countries, than within a single country, as in Miner's case. But even there, it is likely that some institutions and firms receive IPs more generously than normal users. Servers also tend to have more IP addresses than workstations.

The last dimension of interest in this discussion is the extend and way of Internet usage. While the discussion before was centered around capabilities, at the end of the day the actual application is what matters. On the micro-level there is one strain of literature (Pantea and Martens (2013), Goolsbee and Klenow (2006)) concerned with the time spent online as measure of Internet availability. In these papers utility is derived from the product of time and capital investment in IT. However, today the marginal costs of Internet usage is approaching zero in developing countries and is common for all users, due to common flat-rate tariffs. Consequently, the variability results only from differences in time constraints. In addition, there are countless application specific studies on the micro level measuring adoption of a specific technology. One of these is Hitt and Tambe (2007), who study the access to different categories of websites.

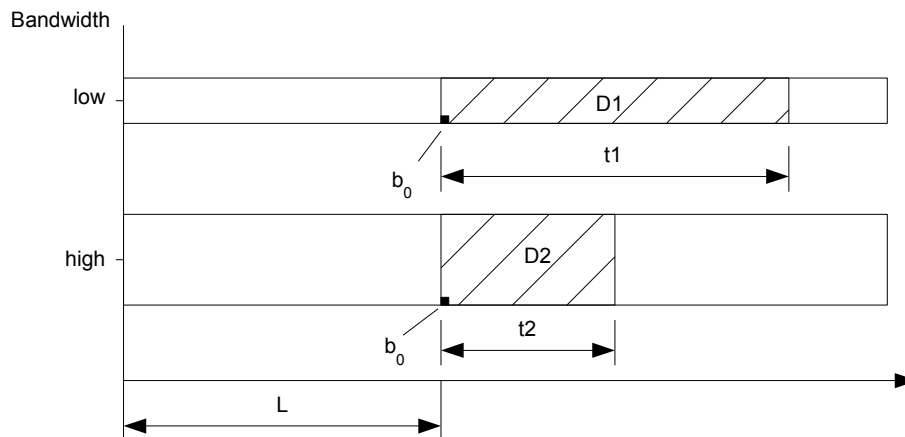
2.2. The Latency and Bandwidth Relationship

If one wants to measure the quality of Internet infrastructure, rather than its application, the usage of bandwidth and latency is a plausible alternative. These two values add up to the *experienced* Internet speed and are closely related. Figure 2 shows the relationship between the two measures, for a download of files of the same size ($D_1=D_2$) using a hypothetical low and a high bandwidth connection.

Both bars in the diagram are hypothetical cables with a high and respectively a low bandwidth. And shows the flow of data through the cable over a time period t . After a user has requested some data some time L before the data arrives. Afterwards there is some time during which data arrives (t_1 or t_2). Apart from the actual transmission times (t_1 and t_2) there might be other data transmitted which is not of interest in this example.

³For one current example from Germany see the recent policy of the cable provider Unitymedia who do no longer provide a IPv4 Address per connection <http://www.onlinekosten.de/news/artikel/51398/0/Unitymedia-Neukunden-erhalten-nur-noch-IPv6-Adressen>.

Figure 2: Relationship between Latency and Bandwidth



Source: Own work loosely based on <http://zoompf.com/blog/2011/12/i-dont-care-how-big-yours-is>

Latency (L) is the time for the first bit (e.g. b_0) to reach its recipient. Its determinants are the technology used for transmission, distance and number of routers on the way and their respective load. The lower bound is given by the speed of light in a fiber optic cable. Consequently, if one wants improvement on that end, the only possibility are shorter, more direct cables. On the other end there are improvements to be made by increasing router capacity, which would potentially hold packages longer if the throughput is insufficient. It is important to note that latency (L) is independent of the transmission time (t_1 and t_2) and bandwidth, while bandwidth effects transmission times.

Bandwidth is the throughput of data usually measured in (mega)bits per second and is commonly the measure associated with the term "Internet connection speed". It has greatly expanded in recent years. Latency on the other hand has only gradually improved. For most ordinary applications the user will receive his disutility from the sum of latency and transmission time. Hence, improvements in latency and bandwidth are to some degree substitutes. Improving latency is rather costly, while increasing the bandwidth is comparatively cheap, as latency reducing measures mostly come from more direct cables. As a consequence, latency increasingly matters for the transfer of small amounts of data in high bandwidth networks, as the actual transmission time tends towards zero as bandwidth increases. and only latency remains as "waiting time", that the user experiences when surfing the web.⁴

⁴The share of latency in total transmission time is $\frac{L}{L+t}$. With technological advances the transmission time of small amounts of data tends towards zero. Hence, the relative importance of latency approaches unity.

The ability to substitute these two inputs depends on the application. In particular synchronous communication relies on (reasonable) short latency. In particular voice communication relies on instant feedback for the speaker. Also for financial transactions a low latency is of uttermost importance.⁵ When watching a TV stream online, it may not be important for the viewing experience itself, whether one receives the data a few seconds later. However, hearing the neighbors (who might use a classic terrestrial antenna for TV reception) cheer before one does even sense an attempt by a striker in live broadcasted football match, might diminish the own enjoyment from watching the world cup final.⁶

When measuring bandwidth, the method of aggregation is crucial. The international bandwidth per country as it is used in this paper is available from the ITU (International Telecommunication Union). It is a good measure to reflect potential technological bottlenecks, by comparing the bandwidth between countries. The international bandwidth is important as the majority of content providers reside in single countries (e.g. the United States or Ireland). On the other hand, Halavais (2000) finds that a lot of connections (in his case web links) are local. Hence, for a lot of applications (e.g. surfing the web) the rest of the world does not matter very much, while for centralized services like YouTube it might be of great importance. However, the relative importance of the local hosting industry might differ between developing and developed countries. In developing countries, where domestic hosting services are unreliable, international bandwidth is likely of greater relative importance. This is due to the fact that users tend to use foreign provided ICT services if the local options are limited or unreliable. One example is the popularity of French E-Mail providers in Africa.

2.3. Description of the Latency Data

In the first parts of this paper the use of latency data as a proxy for Internet quality was proposed. In order to analyze the suitability, the empirical part of this paper mainly employs data from Carna Botnet (2013). The authors used a program to infect thousands of embedded computers with trivial default passwords settings, which were used to scan the whole Internet. The usage of compromised devices gave them access to a huge bandwidth, which allowed to perform bandwidth intensive tests and contact every host multiple times from different places around the earth throughout the last quarter of 2012.

⁵Some background information are available at <http://www.informationweek.com/wall-streets-quest-to-process-data-at-the-speed-of-light/d/d-id/1054287?> accessed 11.02.2015

⁶Zota (2014) showed the latency differences for Internet-based broadcasts in the wake of the of the 2014 Fifa World Cup

This analysis focuses on the measure of ICMP⁷ echo-requests, which yields the latency for a transmission between two clients. The requesting host sends out an echo-request (Ping) and the recipient answers with an echo-reply (Pong). The measured round-trip-delay is the latency between request and reply. It depends on the electrical signal transmit time, hence on distance, and more importantly on queues and processing in routers. The target hosts were assigned randomly and contacted multiple times from different sources. This means that the latency between one host and one random host on the Internet, should guarantee representative measures for the Internet as a whole.

Data preparation and aggregation In a first step the ICMP data from Carna Botnet (2013) has been purged of records indicating no response from the host. This could be for two reasons, either the IP Address is not assigned or the host was offline at the time of the connection attempt. As there were several attempts to connect a certain hosts, chances are that it has been reached at least once. Nonetheless, it is likely that machines which are always on, are over-represented in the sample. Moreover, these machines are likely to have a faster connection (e.g. at government offices, telecommunication companies or universities) than those connected via dial-up. As this pattern would be the case for most countries, it should not influence the results on a cross-country basis.

I aggregated the data on a per-IP basis and using Maxmind's GeoLite database⁸ linked it to the country of origin. Out of the 594,050,059 hosts it was impossible to determine the location of 194,415 hosts in addition to 63,000 hosts associated with *Anonymous Proxy* service and no clear location. In order to reduce the number of observations to a manageable dataset I sampled the data on a per country basis and drew a random sample of 100,000 per country. For countries with fewer observations, the whole population is included. The distribution of latency in the sample is positively skewed. Hence, I used the median in the process of aggregation to mitigate the influence of outliers.

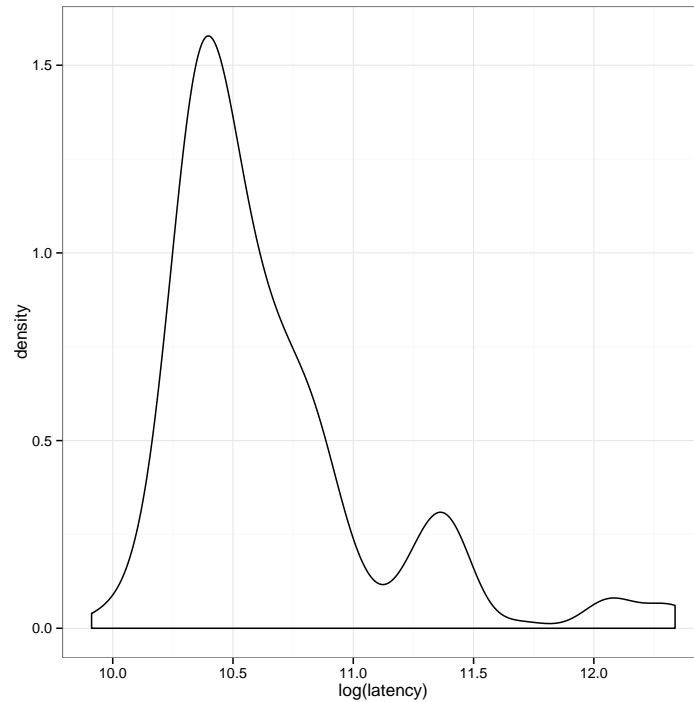
Visualization and descriptive Statistics The skewed distribution found within countries prevails for the country medians on inter-country level (see Figure 3).

The map in Figure 4 shows the geographical distribution of latency. As one would expect latency is high in Africa, South America, and parts of Asia, reflecting the general level of economic develop-

⁷The Internet Control Message Protocol, is used to transmit error and control messages in an IP based network.

⁸<http://dev.maxmind.com/geoip/legacy/geolite/> accessed June 10th 2013

Figure 3: Distribution of Median-Latency across countries

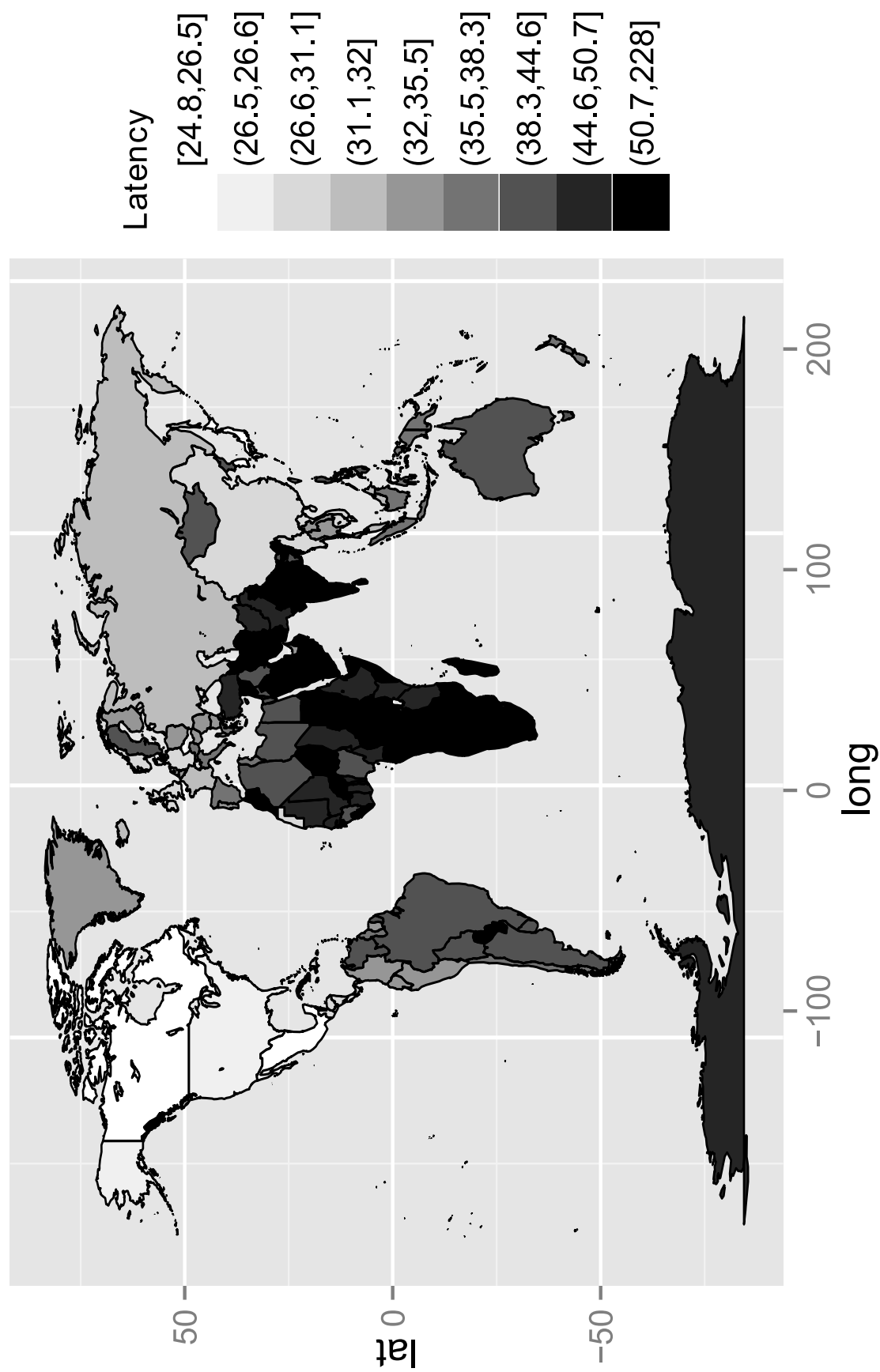


ment in these regions. More surprising is the low latency found in Western Sahara and South Sudan (not mapped). These findings coincide with a very low number of observations for these countries. As a consequence measurement errors are likely e.g. the computers in question might not even be located inside the border of the territories in question. Internet quality within these countries are likely comparable to (or slightly worse than) Morocco and respectively Sudan, who are or were in charge of the administration of the territories.

Data quality and ethics Krenc et al. (2014) discuss data quality of the data set. They point out that the methodology used to collect the data, was the novel part of the project and the reason for the media buzz, as complete scans of the Internet had been conducted earlier. I argue that only the used random assignment and various computers used as probes for the scan, allow to reflect the connectivity of a country to the whole Internet rather than to single reference points.

The data quality issue which they find, might be a concern, depending on the use of the data. In particular, they explained that it is difficult to disentangle the different waves of scans. I believe that on an aggregate level, e.g. the comparison of country medians in this paper, the uneven number of scans (resulting from incomplete waves) and unequal intervals are of minor importance. However,

Figure 4: Geographic distribution of Latency



Note: For the sake of readability, latency is reported in milliseconds here, instead of representing the raw data in microseconds.

it remains a concern if one would pursue an analysis using the number of ip-adresses, hosts or computers.

A last important question Krenc et al. touch upon is whether the usage of such “illegally obtained” data might be used from an ethical point of view, and what ethical codes of conduct apply when dealing with the data. They find that there is no consensus on this topic yet. I feel confident that this data may be used as no harm was done and the data is available publicly. Moreover, in the domain of econometrics of crime data gathered by criminals appears to be publishable e.g. Levitt and Venkatesh (2000). In this publication I deal with highly aggregated per country medians, implying that the publication of the results and data used in the analysis does not interfere with the privacy of individuals.

Comparison An interesting comparison can be made between median latency, bandwidth per user and Share of Internet Users.⁹

In Table 1 and 2 the countries with are ranked according to each indicator and the top and bottom twenty are shown. There are notable differences between the three rankings. It is striking that countries in Middle America are doing well in terms of Latency, while the top twenty list for Bandwidth per User is dominated by European countries. A peculiarity is the case of Cambodia, which ranks 10th in terms of latency but has the fifth lowest share of Internet Users. Unfortunately, there is no easy explanation for the different performance. But there is anecdotal evidence for a governmental investment which does not reach the majority of people yet¹⁰. In later parts of this paper I will examine the relationship between infrastructure and users. Of the countries with bad Internet, most are located in Sub Saharan Africa, South Asia and the Middle East.

⁹Bandwidth per User and Share of Internet Users are taken from the ITU World Telecommunication and Indicator Database

¹⁰The Phnom Penh Post reported on the 16. July 2009 that 2/3 of the country are now covered with fiber optical cable (See: <http://www.phnompenhpost.com/business/fibre-optic-cable-links-regions-data-networks>, accessed 18.06.2014)

Table 1: Countries with the “best” Internet

	Bandwidth per User	Share of Users	Latency
1	LUXEMBOURG	ICELAND	MACAO
2	HONG KONG	NORWAY	HONG KONG
3	MALTA	SWEDEN	JAPAN
4	SINGAPORE	DENMARK	KOREA, REPUBLIC OF
5	ICELAND	NETHERLANDS	MEXICO
6	SWITZERLAND	LUXEMBOURG	CANADA
7	SWEDEN	FINLAND	UNITED STATES
8	PORTUGAL	NEW ZEALAND	BELIZE
9	NORWAY	QATAR	BAHAMAS
10	UNITED KINGDOM	BAHRAIN	<u>CAMBODIA</u>
11	BELGIUM	UNITED KINGDOM	DOMINICA
12	DENMARK	CANADA	GUATEMALA
13	NETHERLANDS	ANDORRA	CURACAO
14	FINLAND	SWITZERLAND	DENMARK
15	ROMANIA	UNITED ARAB EMIRATES	SWITZERLAND
16	AUSTRIA	KOREA, REPUBLIC OF	HONDURAS
17	CANADA	GERMANY	CAYMAN ISLANDS
18	CZECH REPUBLIC	ANTIGUA AND BARBUDA	LIECHTENSTEIN
19	IRELAND	FRANCE	EL SALVADOR
20	SLOVENIA	AUSTRALIA	DOMINICAN REPUBLIC

Table 2: The countries with the worst Internet

	Bandwidth per User	Share of Users	Latency
1	IRAQ	MADAGASCAR	OMAN
2	GHANA	COTE D'IVOIRE	LESOTHO
3	CAMEROON	LESOTHO	SOUTH AFRICA
4	NIGERIA	MOZAMBIQUE	SUDAN
5	MADAGASCAR	<u>CAMBODIA</u>	PARAGUAY
6	ANGOLA	AFGHANISTAN	SYRIAN ARAB REPUBLIC
7	UZBEKISTAN	CAMEROON	KUWAIT
8	AFGHANISTAN	BANGLADESH	SAUDI ARABIA
9	TANZANIA	IRAQ	INDIA
10	SUDAN	RWANDA	NEPAL
11	NEPAL	PAKISTAN	MOROCCO
12	MOZAMBIQUE	LAO	ANGOLA
13	LAO	NEPAL	SRI LANKA
14	YEMEN	INDIA	ZAMBIA
15	ZAMBIA	NAMIBIA	IRAN
16	BANGLADESH	TANZANIA	ZIMBABWE
17	ZIMBABWE	ZAMBIA	MADAGASCAR
18	NAMIBIA	NICARAGUA	NAMIBIA
19	IRAN	UGANDA	MOZAMBIQUE
20	KYRGYZSTAN	ALGERIA	YEMEN

3. Determinants of Internet Adoption

After the discussion on the suitability of different indicators in order to measure Internet usage and quality, as well as the introduction of the data, in the previous section, the current section is dedicated to the determinants explaining Internet use and provision, as measured by the different indicators. The focus of the analysis will be on the novel latency measure, which I proposed in earlier parts of this paper.

3.1. A simple model of Demand and Supply

In order to identify the determinants of Internet infrastructure, I formulate a simple model illustrating the effects of demand and supply factors. The two forces jointly determine the equilibrium level of infrastructure provisioned. The scope of the model lies on providing a framework, which can be utilized the discussed indicators and compare the their determining factors.

Demand is determined by income and access costs, which is the relative price of broadband service with respect to the income.

In the literature there is a debate on other potential other factors influencing demand. Wunnavu and Leiter (2008) make a point that language barriers and education influence the utility gained from using the Internet, as these factors influence the understanding of online material and the amount of information available to the individual user. Nonetheless, in simple economic models it is usually assumed that demand for a good is independent from the utility gained from its consumption.

Assuming the simple case the demand equation only depends on prices and income and take the form of:

$$y_{Di} = f(\text{Income}_i, \text{Price}_i) \quad (1)$$

Supply is determined by the amount of investment and associated costs of construction, the revenue from selling Internet services (Price) and market structure determining the pricing strategy of the firm. Leading to following supply equation.

$$y_{Si} = g(\text{Investment}_i, \text{Cost of Construction}_i, \text{Price}_i, \text{MarketStructure}) \quad (2)$$

In equilibrium demand and supply will be equal leading to: $Y^* = Y_{Si} = Y_{Di}$, which is the value we are likely to observe in the data.

Market structure The market structure and the role of governments varies greatly across countries making it difficult to reflect it accordingly in the supply equation (Röller and Waverman, 2001, p. 917). On the basis of oligopoly theory one would expect market structure to have an impact on prices and quantities. As an example assuming Cournot competition, oligopolists would charge a mark-up over marginal costs. With increasing competition one would expect increased supply and lower prices. On the other hand, a smaller number of firms in the market, might also increase the potential for governments influence.

The government objectives of involvement might also differ across countries and across time. In the past telecommunication had been regarded as a natural monopoly in the past, due to its high fixed costs. Hence, only governmental investments made it possible to supply Internet services. Only during the course of the 1990s governments began to liberalize the telecommunication market (see DICE Database (2009) for an overview), after its operation became economically viable. Alternatively, governments may also artificially prohibit private operators to enter the market. In particular countries with democratic deficits may want to “control” the flow of information.

Consequently, it is convincing that government controlled monopolies differ from markets with private enterprises when the government often follows policy objectives, rather than operate as profit maximizing enterprise. Due to anti-trust regulations, common in market based economies, and the objective of liberalization true profit maximizing monopolies are unlikely to exist.

Röller and Waverman dummy-out the US and Canada in the supply equation "Given the private market driven telecommunications suppliers" (Röller and Waverman, 2001, p. 917). Following their approach, I also include a dummy variable to treat liberalized and non liberalized countries differently. The monopoly-dummy marks countries with just one single provider in order to capture the effect of government intervention in the market.

3.2. Empirical Analysis

The model described above can be estimated by simultaneous equation model, where the demand and supply equation are estimated jointly. In the empirical specification, demand is determined by income (as GDP per capita) and prices, measured by the *monthly charge for broadband connectiv-*

ity. Prices are considered to be endogenously determined by demand and supply, while income is considered to be exogenous.

Turning to the supply equation, the specification is the following: Cost is reflected by a countries population density (people per km²). The idea is that a lower population density would lead to longer cables and, depending on the mean of access, more antennas and other equipment to serve the same number of people. In a recent theoretical paper, Götz (2013) showed that it may indeed be an important determinant of IKT infrastructure provision. As in the demand equation the monthly charge for broadband connectivity is included as a measure of Internet prices.

The investments in ICT infrastructure are aggregated over time, using a perpetual inventory method. The original data from the ITU database only includes investments flows rather than capital stocks. Certain ICT equipment deteriorates fast while, some hardware remains in use for a long time. This is reflected by the discount function e^{-ax} . The calculation is described in more detail in Appendix A.

The data on the monthly charge for broadband connectivity, the share of Internet users in the population and investment in ICT infrastructure originate from the World Telecommunication/ICT Indicators database 2013 (16th edition), while GDP per capita and population density were taken from the World Development Indicators online in February 2014.

Information on the market structure is scarce. As the market structure and degree of competition may differ across countries. Justified by the argument of market power, this is approximated through the number of providers active in the data. However, the data quality on the number of providers might not be very high.¹¹

The following system of equations is jointly estimated by 3SLS treating the price as endogenous, instrumenting it by the exogenous variables not present in the respective equation. Thereby, one accounts for the fact that prices are jointly determined by demand and supply.

$$Y_{Di} = \alpha_0 + \alpha_1 \text{MonthlyCharge}_i + \alpha_2 \log(\text{GDPCap}_i) + \varepsilon_{Di}$$

$$Y_{Si} = \beta_0 + \beta_1 \text{MonthlyCharge}_i + \beta_2 \log(\text{PopDensity}_i) + \beta_3 \log(\text{Stock}_i) + \beta_4 \log(\text{providers}_i) + \beta_5 \text{monopoly}_i + \varepsilon_{Si}$$

¹¹Taken from the 2008 issue of the CIA World Factbook(Central Intelligence Agency, 2008), as current issues do not include information on providers

Results

Table 3 shows the regression results of the SEM model across the different indicators, with OLS results provided for comparison. When comparing the regressions for the different indicators one should keep in mind that latency is a “negative” measure, with 0 ms representing instantaneous transmission. If the covariates had the same effect on the indicator, one would expect the signs of the coefficients to be reversed compared to the Bandwidth and Internet penetration rate.

The price (MonthlyCharge) appears to influence Internet use and quality in a similar manner. The effects appear to influence the results primarily from the demand side, where the coefficients are very similar. A change of one dollar in subscription prices results in a change 0.3% in latency, 0.5% in Bandwidth per capita and 0.4% in the share of Internet users in the population. Income has *ceteris paribus* no effect on effect on latency, while a 1% increase in income leads to 0.7% higher bandwidth per capita and 0.5% increase in the penetration rate.

The effect of population density can only be observed on the latency, where the coefficient is even significant on the 95% confidence level. A one percent higher population density leads to a reduction of latency times of 0.5%.

As expected, there is a significant influence of the accumulated stock of ICT capital on UserShare as well as Bandwidth per User (only on the 10% level) - and the coefficient has, as expected, the opposite sign for the model explaining latency. The magnitude of the effect differs across the three indicators while change in 1.5% Bandwidth per User for a 1% change in ICT capital, it is only -0.13% for latency. The difference in magnitude of two coefficients gives some support to the fact that latency improvements are more difficult to achieve than improvements of bandwidth.

When interpreting the penetration rate - an increase of 1.15% for a 1% increase in ICT capital, the question of reverse causality arises. However, I am convinced that the number of users today does have little influence on the *accumulated* ICT capital of the past years.

The log number of providers in a country appears to be significant in the OLS specifications. While the monopoly dummy for a non competitive market structure is significant for two specification. Having a monopoly or non-liberalized market leads to a 27.6% higher latency and a hypothetical reduction of the share of Internet users in the population by -89.9%.

Table 3: Regression Results (SEM)

	log(Latency)				Log(Bandwidth/User)				log(Users/Pop)			
	OLS		3SLS		OLS		3SLS		OLS		3SLS	
	D	S	D	S	D	S	D	S	D	S	D	S
(Intercept)	11.030*** (0.161)	10.817*** (0.165)	10.936*** (0.503)	10.862*** (0.483)	6.013*** (0.490)	7.815*** (0.695)	3.866*** (0.818)	1.147 (7.770)	-4.729*** (0.290)	-3.172*** (0.454)	-5.158*** (0.579)	-6.699 (4.362)
monthlycharge	0.001** (0.000)	0.000** (0.000)	0.003** (0.001)	0.001 (0.002)	-0.003*** (0.001)	-0.003*** (0.001)	-0.005** (0.002)	0.030 (0.027)	-0.001** (0.000)	-0.000 (0.000)	-0.004** (0.002)	0.021 (0.016)
log(gdpcap)	-0.049*** (0.018)		-0.061 (0.052)		0.482*** (0.055)		0.747*** (0.084)		0.431*** (0.033)		0.504*** (0.059)	
log(PopDensity)		-0.017 (0.012)		-0.051** (0.022)		0.046 (0.052)		0.301 (0.399)		0.047 (0.035)		0.237 (0.190)
log(Stock/Pop)		-0.061*** (0.019)		-0.133** (0.059)		0.438*** (0.078)		1.558* (0.919)		0.415*** (0.049)		1.143*** (0.540)
log(providers)		-0.009 (0.012)		-0.012 (0.028)		0.107* (0.054)		0.435 (0.494)		0.090** (0.037)		0.134 (0.254)
monopoly		0.053 (0.060)		0.244** (0.111)		0.103 (0.265)		-2.172 (2.068)		0.007 (0.180)		-2.259** (0.973)
Adj. R ²	0.130	0.185	-1.249	0.300	0.565	0.436	0.583	-12.127	0.672	0.547	0.399	-14.426
Num. obs.	105	105	105	105	105	105	105	105	105	105	105	105

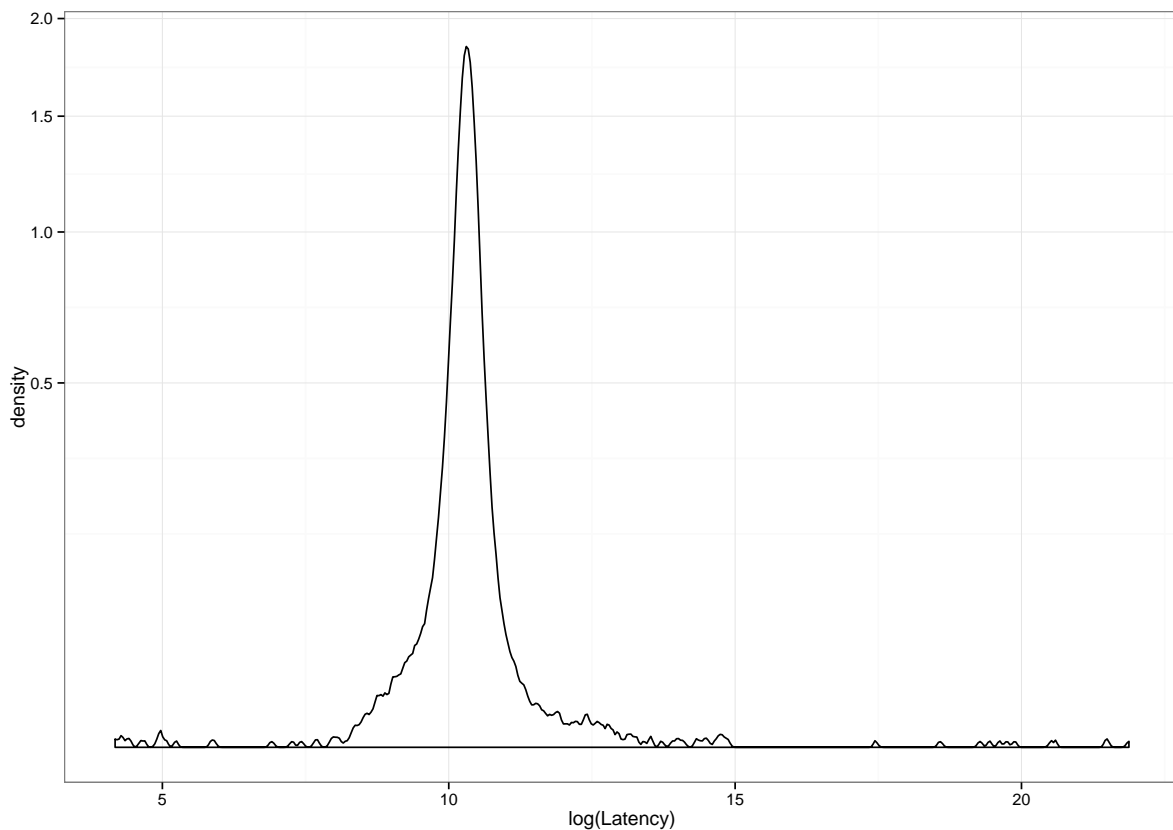
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

As the R^2 is not very useful to interpret in the 3SLS estimation. One can only argue that the R^2 from the OLS estimation hints at the fact the model explains more of the variation of Bandwidth per User and the User share of the population than of latency. This results comes likely from the strong correlation of income with the first two measures and no significant correlation between income and the latter measure.

Different Quantiles

It is obvious that one possibility for differences in results between the different indicators might result from the choice of aggregation method. While penetration rate (User/population) and bandwidth per user are the means, I used the median to analyze the effects on latency. This choice was necessary due to skewed distribution of latency times (See Figure 5 as an example). Hence, the question arises if the effect of the covariates on latency differs if one regards quantiles other than the median.

Figure 5: Distribution of log(Latency) in the Germany



Note: In order to improve readability, the square root is used to scale density.

The results for the 10th and 90th percentile, as well as the 1st and 3rd quartile in comparison to the median is shown in Table 6. For the 3rd quartile and the 90th percentile only price remains significant. In the lower quantiles the effect of population density and the stock of ICT capital becomes stronger compared to median case. Moreover, the coefficient for income becomes highly significant.

Again, it is important to bear in mind that higher percentiles, imply longer latency times and, hence, worse Internet quality. The empirical analysis shows that the model in shown explains supply and demand for “high quality” Internet, while only prices and the intercept remain significant for 75th and 90th percentile.

4. Conclusion

After a brief survey of the existing literature on investment in Internet infrastructure, I introduced a novel measure of Internet quality based on latency. This measure has advantages over existing ones, in particular the widespread use of the share of Internet users. As pointed out, latency is closely related to infrastructure quality. Moreover, its relative importance with respect to bandwidth increases when bandwidth becomes large, even for day-to-day activities like surfing the web. Additional advantages include the possibility to measure it directly over the Internet, compared to the survey-based collection of bandwidth and user data. Having data for 247 countries and territories yielded little additional benefit as the analysis is constraint by a large share of missing observations in the explanatory variables, in particular ITU database. Nonetheless for descriptive purposes it is nice to have data for as many regions as possible.

The model developed in this paper explains more of the variation of bandwidth per user and the user share rather than of latency. There are notable differences in the correlation between the measures of Internet availability and quality and the explanatory variables, which supports the idea that each measure is related to a distinct aspect of Internet quality. Consequently, the measures also differ in terms of policy implications. Latency can only be improved by shorter fiber optic cables, which require a certain population density to be cost effective. The fact that bandwidth and user share are strongly correlated with income appears reasonable, as both measure can easily be improved by additional connections to neighboring countries, which might be the result of a higher level of competition in the market. The share of users could be increased by supporting Internet Cafes, supporting Internet access in public institutions or subsidizing private Internet connections.

Both goals might be easy to achieve in the capital, whereas improving median latency is costly. The empirical analysis has shown, how one could improve Internet quality for lower quantiles (e.g. where latency is relatively low), we learn rather little about the long tail of high latency. Either these cases are rather heterogenous or other determinants are at work which determine high latency.

Unfortunately, it is impossible to make any inference about causality in the cross section. Nonetheless, I hope that my contribution provokes additional research in the field of measures of Internet quality, in order to put the discussion on digital divide on a more solid footing.

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A. Estimation of accumulated capital stock

Regarding ICT investments, the ITU database only includes the investments flows in a given year. However, ICT capital can be used for a number of years until it is depreciated. ICT hardware is not homogeneous, as certain equipment last only a short period of time while others (e.g. cables) are used over several years or even decades. To reflect these features the stock of ICT capital is estimated using the following exponential function:

$$\text{Stock}_0 = \sum_{t=-\bar{T}}^{t=0} e^{0.1 \cdot t} \times \text{Investment}_t \quad (3)$$

Ideally, one would aggregate the data from the beginning of ICT investment in order to estimate the current capital stock. Ideally, for equation 3 one would set \bar{T} , the point in the past from where one would calculate the capital stock, to ∞ . Due to shortcomings of the data, one has to weight the number of included periods against the loss of observations, as in particular in early periods the data are very scarce. For my estimation I included investment over 10 years ($\bar{T} = 10$). If one would set no cut-off and include all countries regardless of missing observations one would bias the results in favor of countries who have good statistical data.

In order to mitigate the issue of missing data one has to impute the missing values or suffer from bias or loss of observations. The following steps were undertaken to fill in the missing data:

1. For missing observations on the current edge (as well as for the beginning of the time series), annual investments are assumed constant since the last observation.
2. “Holes”, missing values inside a time series, were imputed linearly. In a panel analysis one should use a multiple imputation method, as standard errors will be too small otherwise. Nonetheless, in this static setting where only the cumulative values are used, this issue can be neglected.

B. Tables

List of variables

BandwidthPerUser International Bandwidth per User, as available from the ITU

latency Latency (mean and quantile as indicated) from the “Internet Census 2012”

nObs Number of IPs per country used to calculate country-wide latency

UserShare The Share of Internet users in the population (also penetration rate)

gdpcap GDP per Capita

providers The number of providers per country

monopoly Dummy for providers=1

Stock/Pop The calculated accumulated stock of ICT capital

Investment Investment in ICT capital per capita (for comparison)

Table 4: Summary Statistics

	mean	median	var	sd	valid.n
LOGlatency.median	10.65	10.51	0.23	0.48	105.00
LOGBandwidthPerUser	9.91	10.13	3.29	1.81	105.00
LOGUserShare	-1.09	-0.72	1.14	1.07	105.00
monthlycharge	69.56	26.60	39454.95	198.63	105.00
LOGStockPop	5.60	5.67	1.71	1.31	105.00
LOGProviders	2.54	2.40	3.46	1.86	105.00
monopoly	0.14	0.00	0.12	0.35	105.00

Table 5: Correlation between Variables

	LOGlatency.median	LOGBandwidthPerUser	UserShare	monthlycharge	LOGgdpcap	LOGStockPop	LOGProviders
LOGlatency.median							
LOGBandwidthPerUser	-0.48***						
LOGUserShare	-0.40***	0.66***					
monthlycharge	0.24*	-0.43***	-0.21*				
LOGgdpcap	-0.40***	0.73***	0.84***	-0.14			
LOGStockPop	-0.48***	0.62***	0.74***	-0.24*	0.79***		
LOGProviders	-0.30**	0.43***	0.46***	-0.19	0.46***	0.37***	
monopoly	0.33***	-0.31**	-0.32***	0.12	-0.18	-0.17	-0.56***

Table 6: Regression Results (Quantiles)

	10th		25th		50th		75th		90th	
	D	S	D	S	D	S	D	S	D	S
(Intercept)	10.691*** (0.245)	10.116*** (0.546)	10.856*** (0.309)	10.488*** (0.489)	10.936*** (0.503)	10.862*** (0.483)	11.046*** (0.596)	10.995*** (0.754)	11.208*** (0.706)	11.192*** (1.117)
monthlycharge	0.002** (0.001)	-0.001 (0.002)	0.002** (0.001)	-0.001 (0.002)	0.003** (0.001)	0.001 (0.002)	0.003* (0.002)	0.002 (0.003)	0.004* (0.002)	0.004 (0.004)
log(gdpcap)	-0.072*** (0.025)		-0.070** (0.032)		-0.061 (0.052)		-0.033 (0.061)		0.004 (0.072)	
log(PopDensity)		-0.105*** (0.028)		-0.087*** (0.025)		-0.051** (0.022)		-0.028 (0.018)		0.002 (0.018)
log(Stock/Pop)		-0.141**		-0.142**		-0.133**		-0.072		0.009
		(0.065)		(0.058)		(0.059)		(0.100)		(0.151)
log(providers)		-0.026 (0.035)		-0.026 (0.031)		-0.012 (0.028)		-0.004 (0.035)		0.002 (0.049)
monopoly		0.203 (0.144)		0.305** (0.129)		0.244** (0.111)		0.086 (0.081)		-0.005 (0.064)
R ²	-0.137	-0.713	-0.614	-0.266	-1.206	0.333	-0.724	-0.122	-0.573	-0.645
Adj. R ²	-0.159	-0.799	-0.646	-0.330	-1.249	0.300	-0.758	-0.179	-0.604	-0.728
Num. obs.	210	210	210	210	210	210	210	210	210	210

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

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