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

by

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Abstract

This paper discusses 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. Based on this measure one might get the idea that the digital divide is narrowing, 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 more on the study of Internet quality and quantity 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.

The possibility to examine the effects of different determinants on individual quantiles is particularly interesting. ICT investment appear to be stronger correlated with lower latency in the upper part of the distribution, while the effect on the lower part is less pronounced. 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

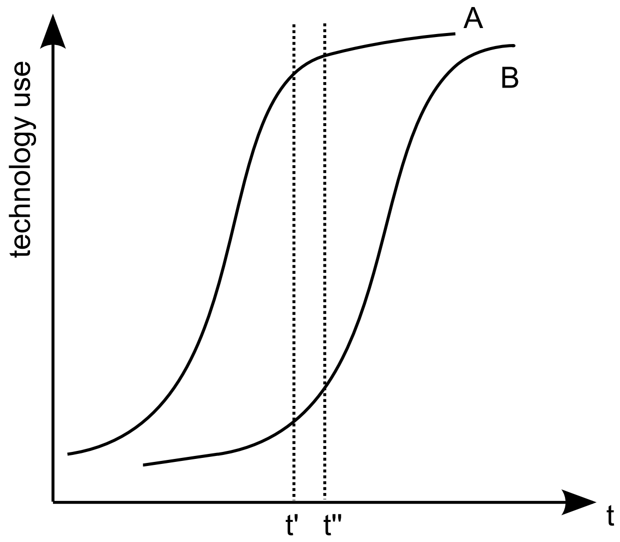


Illustration of the process of Internet diffusion in an industrialized country (A) and a developing country (B)

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 3.1 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, I compare the different indicators in Section 3.2 and determine their causes in a regression analysis before I close with a conclusion in the last section.

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 Röller 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.

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 IPs[1] than Spain (28 millon public addresses[2]). Depending on the actual measurement technique this might also bias the 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,

[1] HP initially was allocated a block of 16 million IPs and recieved 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.

[3] For 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`.

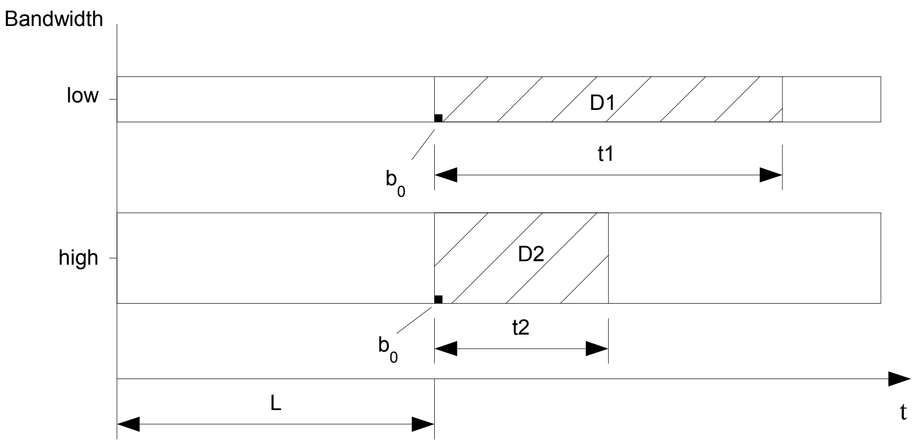
than within a single country, as in Miner's case. But even there, it is likely that some institutions and firms receive IPs more generously than normal users. Servers also tend to have more IP addresses than workstations.

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 (D1=D2) using a hypothetical low and a high bandwidth connection.

Figure 2: Relationship between Latency and Bandwidth



Latency (L) is the time for the first bit (e.g. b0) 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 (t1 and t2) 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 the transfer of small amounts of data in high bandwidth networks, latency increasingly matters, as the actual transmission time tends towards zero as bandwidth increases. Thus, only latency remains as “waiting time”, that the user experiences when surfing the web.[4]

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.

3. Determinants of Internet Adoption

After the theoretical discussion on the suitability of different indicators to measure Internet adoption, this section is dedicated to the determinants explaining Internet use and provision, as measured

[4]The 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.

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. Latency Data

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.

This analysis focuses on the measure of ICMP[5] 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.

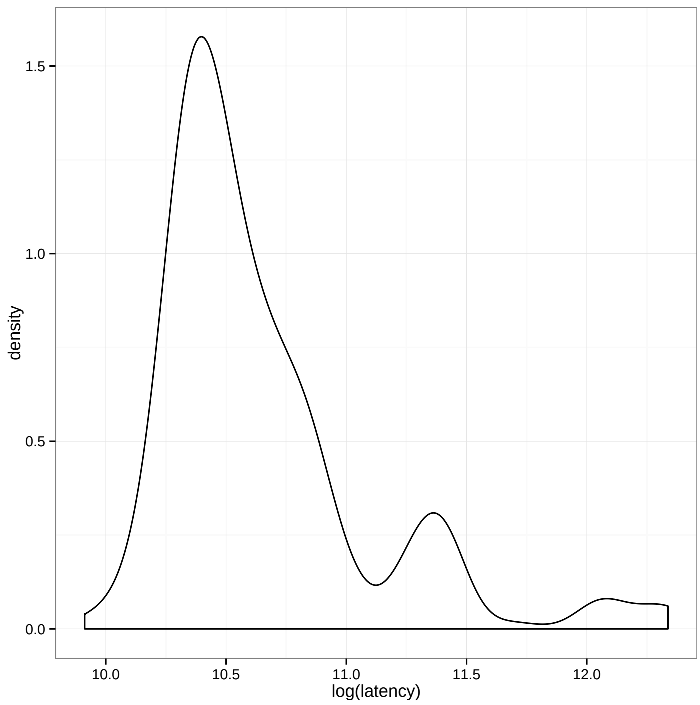
I aggregated the data on a per-IP basis and using Maxmind's GeoLite database[6] linked it to the country of origin. Out of the 594,050,059 hosts it was impossible to determine the location of

[5]The Internet Control Message Protocol, is used to transmit error and control messages in an IP based network.
[6]`http://dev.maxmind.com/geoip/legacy/geolite/` accessed June 10th 2013

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.

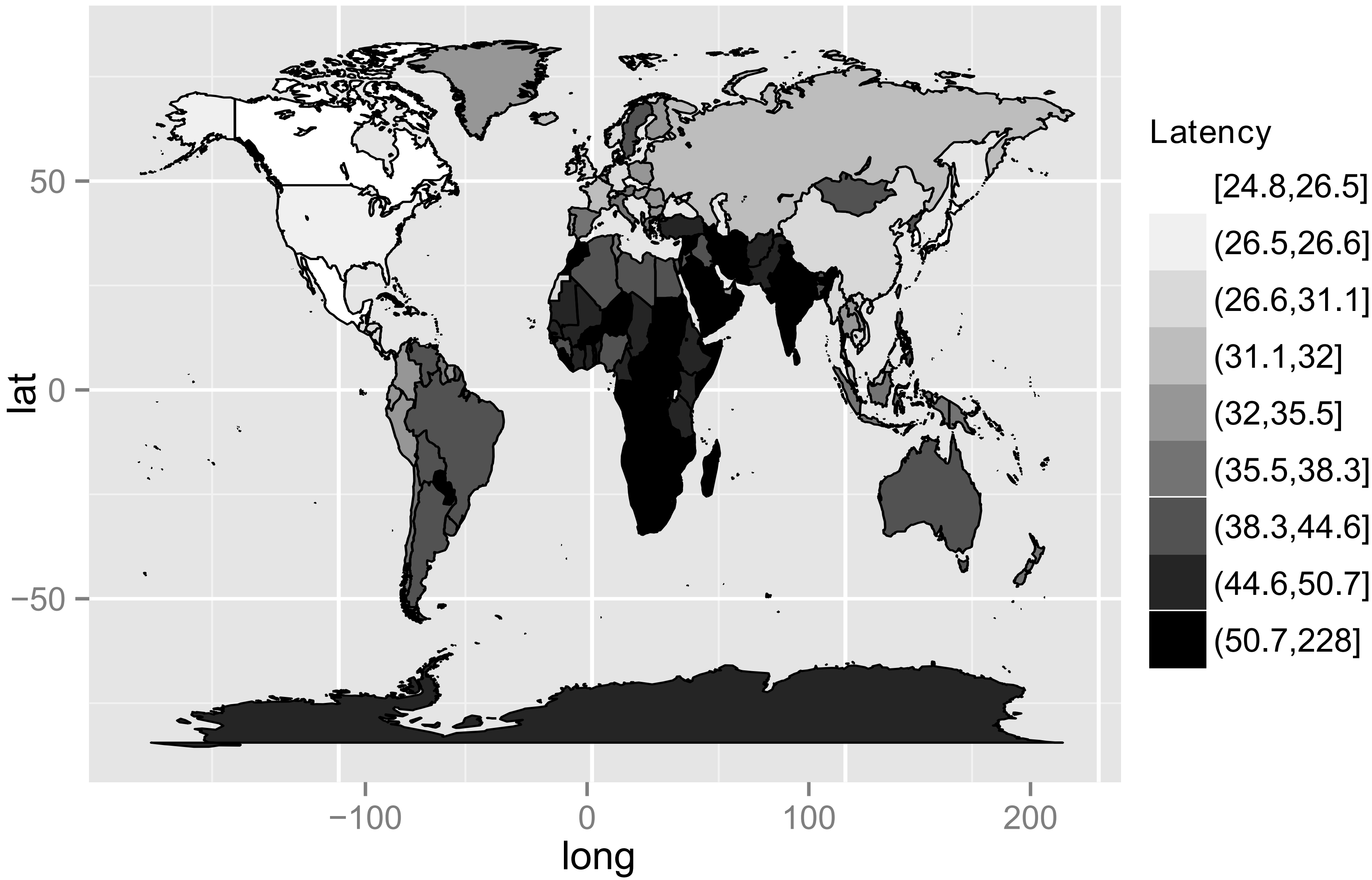
Visualization and descriptive Statistics The skewed distribution found within countries prevails for the country medians on inter-country level (see Figure 3).

Figure 3: Distribution of Median-Latency across countries



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 development 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.

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.

When ranking the countries according to the different indicators (Table 1 and 2, Note: For Latency only countries with more than 10,000 hosts are included), it is surprising that the top twenty countries differ a lot. 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 yet[7]. In later parts of this paper I test for a U-Shape development relationship of infrastructure and users. Of the countries with bad Internet, most are located in Sub Saharan Africa and the Middle East.

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	CAMBODIA
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

[7]The Phom 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 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	CAMBODIA	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

3.2. Estimation and Results

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. It is important to emphasize that the objective is not to accurately reflect the market dynamics and firm behavior. Rather, the model is supposed to provide an example to utilize the discussed indicators and compare the determining factors.

Demand is determined by income and access costs, which is the relative cost of Internet. This equation could theoretically be extended by measures reflecting the benefit derived from Internet use. However, the availability of data, in particular on education, is limited and education is to a large extend correlated with income. Hence, I stick with the basic demand equation:

$$y_{Di} = f(\text{gdpcap}_i, \text{MonthlyCharge}_i) \quad (1)$$

Supply is determined by the amount of investment and associated costs of construction. population density. Röller and Waverman (2001) used geography area as a proxy for cost of access. In their analysis a US-Canada dummy captures the fact that these two country had good communication technology, in spite of being large in size. Rather than following the Röller and Waverman approach, this paper uses population density in order to reflect the costs associated with connecting a single household. This role of population density has recently been emphasized by Götz (2013).

ICT infrastructure may not be as long lasting as conventional infrastructure, but it delivers returns over a few years. The ITU database only includes investments into infrastructure, rather than the stock of ICT capital. Consequently, the cumulative capital stock is derived by using a perpetual inventory method. Since, typical usage times of ICT hardware is rather short the data is discounted using the following function.

$$\text{Stock}_0 = \sum_{-\bar{T}}^{t=0} e^{0.1 \cdot t} \times \text{Investment}_t \tag{2}$$

Ideally, one would aggregate the data from the beginning of ICT investment in order to estimate the current capital stock. Ideally, for equation 2 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 observations with unequal numbers of periods one bias the results in favor of countries who have good statistical data. Missing observation are a problem in the ITU data. At the current edge missing values were replaced with existing past values were used. "Holes" were imputed by linear imputation.

On the basis of oligopoly theory one can expect market structure to have an impact on prices and quantities. Under the simple example of Cournot competition oligopolists would charge a mark-up. With increasing competition one would expect increased supply and lower prices. However, market structure and the role of governments varies greatly across countries (Röller and Waverman, 2001, p. 917). Due to the high fixed-costs for providing the infrastructure, telecommunication has been regarded as a natural monopoly in the past. During the course of the 1990s governments began to liberalize the telecommunication market (see DICE Database (2009) for an overview). As a comprehensive model of competition and government interference would be a rather ambitious project, this analysis only includes the number of providers and a monopoly dummy. I am convinced that government controlled monopolies differ from markets with private enterprises, as the government often follows policy objectives (may it be censorship or development). Due to anti-trust regulation and the objective of liberalization there are no markets with true profit maximizing monopolies.

$$y_{Si} = f(\text{Stock}_i, \text{PopDensity}_i, \text{providers}_i, \text{monopoly}_i) \tag{3}$$

The combination of demand and supply leads to the empirical specification illustrated in Equation 4. The variables determining Internet quality in country i (y_i) are the population density (people per km^2), income measured as GDP per capita, the monthly charge for broadband connectivity as a measure of Internet prices, the number of providers[8] per capita, and investment in ICT infrastructure as a share of GDP.[9] The corresponding estimates are shown in Table 3. In addition to the OLS estimate I use the fractional logit approach proposed by Papke and Wooldridge (1996) in order to account for the fact that the dependent variable UserShare is a fraction and bound between zero and one.

$$\begin{aligned} y_i = \beta_0 + \beta_1 \times \log(\text{PopDensity}_i) + \beta_2 \times \log(\text{gdpcap}_i) + \beta_3 \times \log(\text{MonthlyCharge}_i) \\ + \beta_4 \times \log(\text{providers}_i) + \beta_5 \text{monopoly}_i + \beta_6 \times \log(\text{Stock}_i) + \mu_i \end{aligned} \tag{4}$$

The determinants of latency differs from the determinants of the other two indicators. UserShare and international bandwidth per user are determined by demand side factors GDP per capita and prices, as well as the supply-side factor stock of ICT capital. Whether the number of providers has a significant effect on the share of Internet users depends on the specification. In the OLS estimation there is a small negative effect of having an additional telecommunication provider in the market. A similar effect can be found for bandwidth per user. The negative sign of the number of providers is a little surprising at first sight, as one would expect that a higher level of competition would lead to an increase in quantity. One possible explanation are forgone scale effects, as every firm in the market needs to pay its fixed costs. One might also argue that coordination difficulties are potentially large in ICT, as data packages need to be transmitted between the networks of the different providers.

[8] Taken from the 2008 issue of the CIA World Factbook(Central Intelligence Agency, 2008), as the data are removed from current issues.

[9] The monthly charge for broadband connectivity, the share of Internet users 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.

Table 3: Regressions to Compare Indicators

	Dependent variable:			
	UserShare/100		log(BandwidthPerUser)	log(latency)
	glm: quasibinomial link = logit	*OLS*	*OLS*	*OLS*
	(1)	(2)	(3)	(4)
log(PopDensity)	0.002	0.003	0.018	-0.072^{***}
	(0.041)	(0.008)	(0.082)	(0.027)
log(gdpcap)	0.720^{***}	0.142^{***}	0.708^{***}	0.009
	(0.058)	(0.010)	(0.108)	(0.064)
log(monthlycharge)	-0.223^{***}	-0.030^{***}	-0.530^{***}	0.023
	(0.068)	(0.010)	(0.170)	(0.046)
providers	-0.0001	-0.00001^{**}	-0.0001^{***}	-0.00003^{**}
	(0.0001)	(0.00000)	(0.00003)	(0.00001)
monopoly	-0.262	-0.016	-0.567	0.350^{**}
	(0.188)	(0.034)	(0.348)	(0.165)
log(Stock/Pop)	0.195^{***}	0.036^{***}	0.086	-0.151^{*}
	(0.064)	(0.012)	(0.108)	(0.084)
Constant	-6.571^{***}	-0.802^{***}	5.456^{***}	10.603^{***}
	(0.605)	(0.109)	(1.136)	(0.428)
Observations	105	105	105	105
Adjusted R^2		0.870	0.625	0.307
F Statistic (df = 6; 98)		116.622^{***}	29.929^{***}	8.669^{***}

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Std. Errors in parenthesis, robust errors for OLS estimates

This requires technical and administrative coordination, which is easier if the number of market participants is low.

The effect of the stock of the ICT infrastructure is straight forward. If investment in the current year were used, the question of endogeneity would arise. However, stock of ICT infrastructure, accumulated over a couple of years, is largely exogenous to the number of users in a specific period. As expected, there is a positive impact of ICT capital on UserShare as well as Bandwidth per User.

When measuring Internet quality in terms of latency the results are very different. GDP per capita and prices do not have a significant effect. Recalling that for latency lower values imply better quality, we find that more providers lead to better Internet quality. In addition the monopoly dummy is significant and has a positive sign, indicating that monopolies are associated with worse Internet quality. ICT capital has a positive influence on Internet quality only at the 10 % level, while there is a highly significant effect of population density on Internet quality, confirming the hypothesis by Götz (2013). The explained variation differs substantially across the regressions. While about $3/4$ of the variation of the share of users is explained by the model, only $1/4$ of the variation of latency is explained, which hints at the fact that the impact of GDP on the measure is less pronounced.

Apart from the mean, the effect of demand and supply factors on individual quantiles of the latency distribution within a country can be examined. For that matter I estimated the model with the 10th and the 90th percentile as well as the 1st and 4th quartile of the latency as dependent variable. Table 6 with the results can be found in the appendix. The most interesting finding is that the role of the ICT capital stock is more important for the upper quantiles. The absolute value of the coefficient is increasing in the quantiles. The coefficient for the 90th percentile (-0.201) is almost four times the value of the 10th percentile (-0.059). Apart from that we observe that prices (*MonthlyCharge*) is significant for the 10th percentile and the first quartile. It seems sensible that the price elasticity of demand is higher for lower income countries.

Relating to the distributional considerations, a remaining concern is that one should consider the *mean* of latency when comparing it to the *mean* of bandwidth. However, regressing the same determinants on the mean of latency leads to a R^2 close to zero and a F-Test for joint significance where the null can not be rejected at conventional levels. The likely reason for the findings is the skewed distribution of the data.

Table 4: Regressions to Examine Relationship between Infrastructure and Users

	Dependent variable:			
	log(latency.median)		log(BandwidthPerUser)	
	(1)	(2)	(3)	(4)
log(UserShare)	0.061	0.469***	−0.333	−1.605***
	(0.062)	(0.178)	(0.233)	(0.589)
log(UserShare)^2		−0.093**		0.289**
		(0.042)		(0.125)
log(PopDensity)	−0.073***	−0.074***	0.025	0.027
	(0.027)	(0.028)	(0.080)	(0.079)
log(gdpcap)	−0.018	0.059	0.857***	0.619***
	(0.069)	(0.072)	(0.167)	(0.187)
log(monthlycharge)	0.036	0.026	−0.602***	−0.570***
	(0.050)	(0.048)	(0.176)	(0.164)
providers	−0.00003***	−0.00003***	−0.0001***	−0.0001***
	(0.00001)	(0.00001)	(0.00004)	(0.00004)
monopoly	0.371**	0.396**	−0.690**	−0.768**
	(0.163)	(0.160)	(0.310)	(0.300)
log(Stock/Pop)	−0.159*	−0.146*	0.129	0.089
	(0.082)	(0.081)	(0.111)	(0.105)
Constant	10.609***	9.724***	5.445***	8.201***
	(0.430)	(0.499)	(1.165)	(1.780)
Observations	105	105	105	105
Adj. R^2	0.307	0.334	0.630	0.649
F	7.593***	7.520***	26.328***	25.089***
	(df = 7; 97)	(df = 8; 96)	(df = 7; 97)	(df = 8; 96)
Note:				*p<0.1; **p<0.05; ***p<0.01 robust std. errors in parenthesis

A final issue I want to examine is the relationship between the infrastructure quality, in terms of latency and bandwidth, and the number of users. The results in Table 4 show a significant effect, when adding the number of users and the squared number of users to the model. There are two possible interpretations which can not easily be disentangled in the cross section. First of all, one can argue that there is evidence in favor of network effects. This would mean that the demand for ICT infrastructure is increasing in the number of users in the population one could potentially communicate with. However, the squared term (with a negative sign) points towards a more complicated relationship between the two variables. A plausible explanation would be that there are some initial government investments in infrastructure and initially very few users, resulting in a good infrastructure user ratio and consequently fast Internet. As the number of users increases (consider the s-shape adoption curve), infrastructure improvements cannot keep pace, in particular when Internet gets to rural areas, and quality measures turn bad. Only in the final stage do the quality indicators improve again. To disentangle the two effects one would need to identify the direction of causality, which would require a more extensive data set. The importance of the quadratic term, makes the story about the development path more plausible. Nonetheless, the existence of network effects can not be ruled out, and it is likely that both effects exist and only the net-effect can be observed in the data.

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.

Explaining latency empirically turns out to be more difficult. The model developed in this paper explains more of the variation of bandwidth per user 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. Bandwidth can 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. However, the actual outcome might depend on improving all three measures at the same time. In particular the correlation between Infrastructure quality and the number of users emphasize this issue, and show a U-shaped development path for this relationship.

Additionally, the possibility to look at per-country quantiles rather than averages will be beneficial for policy analysis addressing digital divide. Just by definition, the differences are most effectively reduced focusing on the lower and upper quantiles rather than median or mean values. Unfortunately, a higher ICT capital stock is more beneficial to the upper quantiles, while prices seem to matter more for the lower quantiles.

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. For future research it will be of interest to see if a relationship of growth and latency exists in the data. It is not unlikely that the several measures discussed in this paper have diverse effects on economic development and function through different channels. Hence, the identification of channels through which these potentially affect economic development would be a logical step in the comparison of indicators.

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A. 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 5: Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
BandwidthPerUser	114	94,651.700	399,331.300	41.790	4,091,440.000
latency.median	115	49,441.170	41,209.080	20,173.610	228,109.800
nObs	115	77,033.310	37,866.830	420	100,000
UserShare	114	47.148	28.885	1.408	96.000
PopDensity	115	0.001	0.003	0.00000	0.020
gdpcap	112	13,350.900	16,918.540	253.750	80,007.070
providers	112	167.938	931.525	1	7,000
monopoly	112	0.152	0.360	0	1
Stock/Pop	110	492.264	478.420	1.169	2,047.335
Investment	115	76.424	85.420	0.066	551.797

Table 6: Latency-Quantiles

	Dependent variable:					
	log(mean)	log(0.10)	log(0.25)	log(median)	log(0.75)	log(0.90)
	(1)	(2)	(3)	(4)	(5)	(6)
log(PopDensity)	−0.054	−0.068***	−0.062***	−0.072***	−0.109***	−0.097*
	(0.039)	(0.021)	(0.017)	(0.027)	(0.039)	(0.050)
log(gdpcap)	0.073	−0.038*	−0.032	0.009	0.062	0.109*
	(0.060)	(0.022)	(0.033)	(0.064)	(0.065)	(0.066)
log(monthlycharge)	−0.042	0.095**	0.070*	0.023	0.009	0.030
	(0.067)	(0.039)	(0.035)	(0.046)	(0.056)	(0.073)
providers	−0.0001	−0.00002***	−0.00002***	−0.00003***	−0.00004	−0.0001***
	(0.0001)	(0.00001)	(0.00001)	(0.00001)	(0.00003)	(0.00003)
monopoly	0.308	0.096	0.219*	0.349**	0.278*	0.276
	(0.221)	(0.102)	(0.113)	(0.165)	(0.163)	(0.193)
log(Stock/Pop)	−0.147**	−0.059**	−0.076*	−0.152*	−0.187**	−0.201**
	(0.066)	(0.027)	(0.043)	(0.085)	(0.079)	(0.080)
Constant	11.436***	9.865***	10.251***	10.607***	10.405***	10.638***
	(0.568)	(0.258)	(0.222)	(0.429)	(0.618)	(0.712)
Observations	106	106	106	106	106	106
Adjusted R^2	0.044	0.480	0.457	0.313	0.149	0.067
F (df = 6; 99)	1.813	17.183***	15.726***	8.990***	4.064***	2.266**

Note: *p<0.1; **p<0.05; ***p<0.01
robust std. errors in parenthesis

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