The bad news is that the digital access divide is here to stay:

domestically installed bandwidths among 172 countries for 1986 – 2014

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Highlights:

- The digital divide measured in terms of bandwidth it not closing
- Inequality fluctuates up- and down with technological progress and diffusion
- Asia increased its global share in installed bandwidth from 23 to 51 % in 30 years
- Bandwidth inequality is closely linked to income, which is notoriously unequal
- It is urgent to start measuring bandwidth, not merely counting subscriptions

Abstract

In contrary to the common argument that the digital access divide is quickly closing and that the focus should shift to skills and usage, this article shows that access to digital communication is a moving target unlikely to ever be solved. While the number of subscriptions reaches population saturation levels, the bandwidth divide continuous to be dynamic. The article measures the nationally installed bandwidth potential of 172 countries from 1986 to 2014. The overarching finding is that the divide in terms of bandwidth does not show any clear monotonic pattern. It fluctuates up and down over the decades as the result of an intricate interplay between incessant technological progress and diffusion of technology. The bandwidth divide between high- and low income countries has first increased and only decreased below historic levels very recently during 2012-2014. In general it shows that the bandwidth divide is linked to the income divide, which is notoriously persistent. The bandwidth distribution among all countries is undergoing a new process of global concentration, during which North America and Europe is being replaced by Asia as the new global leader. In 2014 only 3 countries host 50 % of the globally installed bandwidth potential (10 countries almost 75 %). The U.S. lost its global leadership in 2011, being replaced by China, which contributes more than twice as much national bandwidth potential in 2014 (29 % versus 13 %). Despite this bad news about the continuous persistence of the digital access divide among countries, exploratory analysis from a global perspective brings the good news that many more individual people seem to enjoy more equal access to global bandwidth. All of this showcases the urgency to systematically develop indicators to track the digital divide in terms of bandwidth.

1. Introduction

The article takes inventory of the evolution of the international telecommunication infrastructure in terms of the installed telecommunication bandwidth capacity between 1986 and 2014. This matters both because of the importance of digital technologies throughout the world and the continuous evolution of telecommunication. Telecommunication access solution have evolved significantly during the past three decades, consisting exclusively of fixed-line telephony in the late 1980s, and a plethora of access solution with diverse performance levels. Over the last decade, the literature has increasingly pointed to the importance of bandwidth and especially broadband metrics, which have shown to have important socio-economic benefits (Dutton et al., 2004; Koutroumpis, 2009; Prieger, 2013; Gruber et al., 2014; Lee et al., 2015). Quantifying the digital divide in terms of subscriptions might not be sufficient anymore, as not all subscriptions are equal. In light of this, the key question of this article is if technological progress has rendered traditional metrics of the digital divide obsolete.

1.1. From subscriptions to bandwidth

Traditionally the international digital divide is assessed in terms of telecommunication subscriptions (NTIA, 1995; OECD, 2001; ITU, 2015). On the international level, the most common go-to source are the statistics from United Nations' International Telecommunication Union (ITU, 2014). ITU has undertaken a sustained effort over several decades to collect this data from administrative registries of national telecommunication authorities in a harmonized manner. These same databases have shown that the number of mobile and fixed telecom subscriptions per person are increasingly reaching a certain level of global saturation, including 6.8 billion mobile phone subscriptions worldwide for 7.0 billion people in 2014.

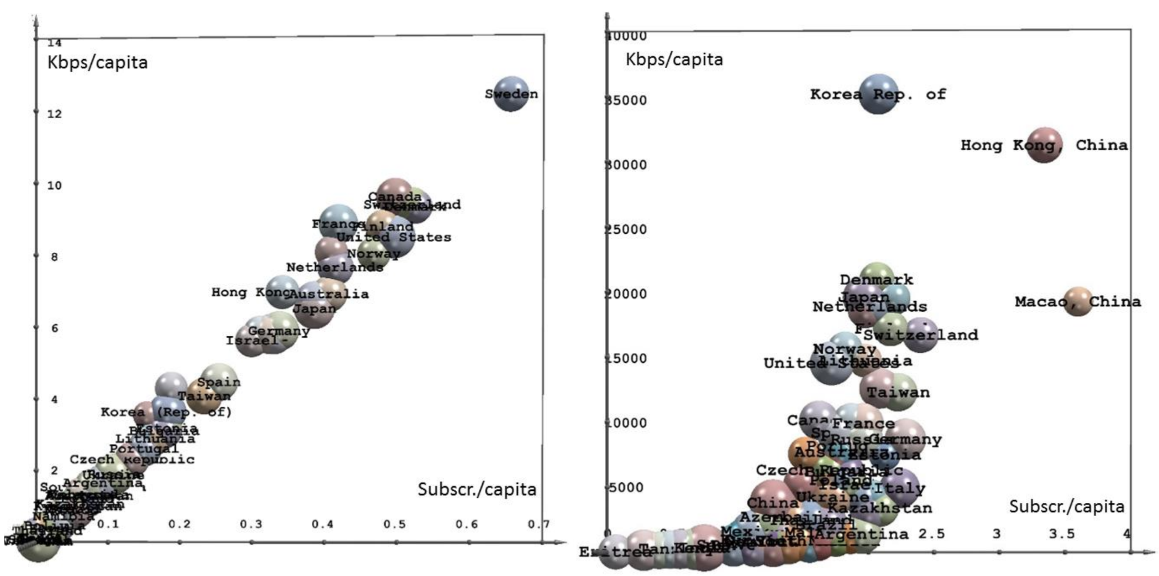
Since there seems to be a certain limit in how many technological devices a person handles (Hilbert, 2014a), any analysis that uses the number of subscriptions as a proxy for the digital divide must come to the conclusion that the divide is closing over time. As early as the year 2000, this perspective has led to the impression that "the gaps are rapidly closing" (Compaine, 2001). Over the years, this view has become as engrained into the way of looking at the digital divide that is has become natural to assume a national "carrying capacity of Internet users" (e.g. Neokosmidis, et al., 2015). Once this carrying capacity is reached (once everybody has reached the limit of how many subscriptions can be handled), saturation sets in and the divide can only close. As a result, new technological solutions might create new divides, but in terms of their numbers the divide will always be closing over time, as it has happened with computer access, mobile phones, or broadband adoption (e.g. Vicente & López, 2011; Loo & Ngan, 2012; Prieger, 2013).

Based on this impression, scholars have long moved on to work on the digital divide in terms of differential usage patterns, caused by differences in skills, culture and other demographics and social variables (Mossberger et al., 2003; Warschauer, 2004; van Dijk, 2005; Vicente & López, 2011; Deursen & van Dijk, 2014). This sometimes referred to as the "second-level digital divide" (Hargittai, 2002; Büchi et al., 2015). In more advanced countries, the dimension of physical access has become a question of technology maintenance to sustain the level of subscriptions and devices (Gonzalez, 2015).

However, the fact that the number of telecom subscriptions per person seems limited and will eventually reach saturation levels does not automatically imply that inequality in terms of access to digitalized information is reducing as well. This is because bandwidth is not uniformly distributed among subscriptions. Figure 1a shows this distinction was not relevant only a few decades ago. The late 1980s exhibited a linear one-to-one relationship between subscriptions and bandwidth, as there was only fixed line telephony around, all with the same bandwidth. Today’s digital infrastructure offers a myriad of different bandwidth options, which leads to an L-shaped non-linear relationship exhibit in Figure 1b. The Figure shows that ICT diffusion seems to hit an invisible wall at around 2-3 subscriptions per person. However, the digital divide continues at this point, just along a new dimension: the bandwidth dimension.

“This implies that we have now moved into a second, more mature, and also more persistent stage of the digital divide” (Hilbert, 2014c). The first phase consisted of a universalization of the required technological infrastructure. The second stage consists of an endlessly evolving inequality of bandwidth. While today almost everybody in the world counts with a minimum level of connectivity potential through a digital mobile phone, some have access to significantly more bandwidth. Figure 1b suggests that there might not be a clear “carrying capacity” in terms of the bandwidth per subscription and therefore also not automatically any level of saturation that would inevitably close the digital divide. The answer to the connectivity question moves from being a binary black-or-white choice (0 - 1) to a continuous and incessantly moving grey zone (1 - ∞).

Figure 1. Subscriptions per capita (fixed and mobile) vs. kbps per capita (voice and data in optimally compressed kbps of installed bandwidth potential). N = 100 countries. Size of bubbles: log population. (a) 1986 (b) 2013.



1.2. So what?

This second stage of the digital access divide becomes extremely relevant in times where fast bandwidth solutions have become to take center stage in the discussion about social growth and progress (Dutton et al., 2004; Koutroumpis, 2009; Prieger, 2013; Gruber et al., 2014; Lee et al., 2015). Bandwidth matters especially for an age of big data, in which the quantity of data (not mere access) have become a driver of social-, cultural-, political-, and economic development (Manyika et al., 2011; Hilbert, 2016). Better understanding the bandwidth divide is also important in order to better frame the ongoing debate about net-neutrality, which centers on the question of creating a tiered internet (Krämer et al. 2013, Hsu, 2014). As it stands, we do not have much insight into internet bandwidth distribution. With or without net-neutrality, it might well be that even without any kind of intervention into traffic patterns, plain differences in physical infrastructure availability around the world have already created a de-facto tiered structure among some with much and some with systematically little bandwidth: a digital bandwidth divide.

Despite these reasons, research continues to disregard this reality and still refers to the number of telecom subscription, especially for large-scale international statistical tests (for example Pick & Sarkar, 2015; Mardikyan et al., 2015; Mendonça et al., 2015). This seems to have less to do with the fact that scholars are not aware, but that subscriptions data is readily available, and bandwidth and traffic data is not. Reminiscent of the famous drunk who is looking for the lost keys under a well-lit lamppost far away from the dark site where the keys were dropped, international analysts continue to recur to the readily available and harmonized databases on subscriptions.

Changing this current practice faces two challenges. One the one hand, important efforts are currently underway to explore new ways to measure relevant aspects of this second stage of the digital divide. Leading authorities like the U.S. Federal Communications Commission (FCC, 2014) or Ofcom (2014) in the UK have started to produce detailed annual reports at the national level. These efforts are struggling with finding adequate new metrics. For example the first generation of broadband reports of the FCC from the early 2000 distinguished between access solution below and above 200 kbps (FCC, 2000). A second generation of reports recognized that "existing definitions are not static" (FCC, 2004), and let to definitions which seem equally temporal in nature, such as distinctions between 200kbps – 2.5 mbps, 2.5 – 10 mbps, 10 – 25 mbps, 25 – 100 mbps (FCC, 2008); or more fine-tuned specifications, which seem as arbitrary as provisional, such as recommendations to measure download/upload ratios at 384 kbps/1.5 kbps and 3 Mbps/768 kbps (FCC, 2012); or later assessments of ratios such as 10 Mbps/1 Mbps and 25 Mbps /3 Mbps (FCC, 2015).[1] Given the lack of a universal metric, it is natural that researchers from academia have started to explore a combination of metrics from private and public sector sources to evaluate the implications of the diverse bandwidth landscape for growth and competition (e.g. Lehr et al., 2011; Libenau et al., 2013). These efforts usually go deep and explore different aspects, but are at the same time usually demographically limited in scope and in the analyzed timespan, since globally harmonized long term time series are not available for more detailed metrics.

On the other hand, the challenge consists in showing why we should care globally about this new dimension of the digital divide. Rather than exploring detailed metrics, these kind of studies ask why is it important to undertake a sustained effort to produce, harmonize and analyze the global evolution of bandwidth (e.g. Vicente & Gil-de-Bernabé, 2010; Hilbert & López, 2011; Riddlesden & Singleton, 2014; Gruber et al., 2014). This present article falls into this second group of research. As such, the article works with a rather rudimentary proxy for bandwidth, but is able to cast a wide global net to show a rough outline

[1] These numbers are often the outcome of a political process, including private sector lobbying influence, e.g. see footnote 133 in FCC (2012).

of ongoing dynamics for 172 countries[2], corresponding to 96 % of the world's population and 99 % of the world's Gross National Income (GNI). The analyzed time series captures 29 years, which covers the entire transition from almost inexistent digitalization (less than 1 % of the global information stockpile was digital in 1986), to the full-blown digital age with almost all of it in digital format (Hilbert & López, 2011).

2. Methodology: a statistical challenge

Much in line with Figure 1, our two most important indicators refer to the number of subscriptions on the one hand, and bandwidth capacity on the other. The undertaking of creating global time series data faces two main statistical challenges, one related to the creation of national statistics among many countries (in space) and the other one to the creation of normalized time series (in time).

2.1. Installed national bandwidth potential

The creation of national bandwidth statistics requires three main inputs: the number of telecommunication subscriptions (fixed and mobile); the kind of access technology per subscription (like DSL, GSM, etc); and the corresponding bandwidth per access technology.

The first two are provided mainly by the well-known database of ITU (2014), which we complement with other sources for a variety of data gaps (especially for the diffusion of fiber optics and wearables and tablets[3]. We include analog and digital fixed-line telephony; fixed-line internet in the form of dial-up, ISDN (Integrated Services Digital Network), DSL (Digital Subscriber Line), Satellite broadband, Cable modem and FTTH/B (Fiber to the Home/Business); 1G, 2G, 2.5G, 3G and 4G mobile telephony (voice and data); and tablets and wearables (see Supplementary Material). This already provides us with one of our main indicators: **the number of subscriptions**. For reasons of simplicity, we will often work with the total number of subscription by adding them all up (neglecting differences in terms of their fixed or mobile nature, and their underlying technology). This does not mean that more fine-grained analysis is not possible (the total is built on the before-mentioned technology rubrics, see Figure 2a), but it most often aims at keeping things simple.

[2] Following 3 letter ISO code: KOR, HK, DNK, JPN, SGP, MAC, NLD, SWE, FIN, CHE, NOR, LTU, USA, GBR, TWN, CAN, BEL, FRA, ESP, DEU, RUS, PRT, AUS, MDA, EST, NZL, CZE, BGR, SVN, HUN, POL, SVK, ISR, ITA, URY, UKR, GRC, CHN, KAZ, SAU, AZE, THA, CHL, TUR, BRA, PRI, MNG, MEX, MYS, ARG, ECU, JOR, DOM, PAN, JAM, MUS, CRI, COL, KGZ, VNM, GHA, ZAF, EGY, NAM, ZWE, IDN, TUN, SLV, NPL, PHL, GTM, PER, VEN, SEN, BOL, PRY, MLI, HND, NIC, IRN, NGA, DZA, UZB, TJK, CIV, IND, KEN, SWZ, PAK, YEM, RWA, CMR, BGD, TZA, MOZ, MWI, SLE, ETH, NER, ERI, ALB, AND, AGO, ATG, ARM, AUT, BHS, BHR, BRB, BLR, BLZ, BEN, BMU, BTN, BWA, BRN, BFA, BDI, CPV, CAF, TCD, COM, COG, COD, HRV, CYP, DJI, DMA, GNQ, FJI, GAB, GMB, GEO, GRL, GRD, GIN, GUY, ISL, IRL, KIR, KWT, LAO, LVA, LBN, LSO, LBR, LIE, LUX, MDG, MLT, MRT, MAR, OMN, PNG, ROU, KNA, LCA, WSM, SYC, LKA, VCT, SDN, SUR, SYR, TGO, TON, TTO, TKM, UGA, ARE, VUT, ZMB.

[3] For example through different regional networks of the Fiber-to-the-Home-Council: http://www.ftthcouncil.org; http://www.ftthcouncil.eu; http://www.ftthcouncilap.org; and Cisco Systems (2015) and Ericsson (2015)

Obtaining the corresponding bandwidth per access technology is trickier. Up until roughly 2006/2007, it was more straightforward to assign a certain bandwidth performance to a specific access technology. For example, a digital fixed-line phone provides a general (uncompressed) bandwidth of 64 kbps, an ISDN BRI internet modem 128 kbps, and the voice-transmission of a GSM mobile phone also 128 kbps. We use this strategy for more traditional technologies, like fixed phones, dial-up, ISDN and 2G/2.5G mobile telephony. After the introduction of global broadband solutions like DSL and cable modem, and 3G mobile telephony, the direct assignment of bandwidth to specific technologies becomes less viable.

We chose to approximate the installed bandwidth by recurring to crowed-sourced data from bandwidth speedtests, which allows us to maintain a very wide geographical focus. Especially NetIndex (Ookla, 2014) has gathered the results of end-user-initiated bandwidth velocity tests per country per day since 01/01/2008. This crowd-source method results in very large samples. For example, an average of 179,822 tests per country per day were gathered in 2010 through Speedtest.net and Pingtest.net. The resulting database is seen as "the best of the currently available data sources for assessing the speed of ISP's broadband access service" (Bauer et al., 2010). We consult both upload and download test and add both in our assessment of broadband capacity. We assume that the national average bandwidth test result from NetIndex for fixed broadband is the weighted mean of all nationally installed DSL, cable modem, and FTTH/B subscriptions. Likewise we assumed that the national average for mobile data from both NetIndex (Ookla, 2014) and Akamai (2014) is the result of 3G and 4G mobile phones. For details see Supplementary Material.

The sum of the product of the number of subscriptions and their respective broadband performance provides a proxy for the installed national bandwidth potential. It is important to point out that this metric does not measure actual traffic flow, but works with the number the end user gets when performing an online speed test at a specific moment in time. This has shown to be significantly better than working with supply side metrics, which are often flawed as operators usually do not fulfill the promised bandwidth (European Commission, 2014). However, it still merely refers to an installed potential, as the result from a second-long speed test might deviate from hour-long downloads, and does not provide insights into how intensively the bandwidth is used (Hilbert & López, 2012b). In reality, the network in its entirety would collapse if all users would demand their installed bandwidth capacity simultaneously (or 24 hours a day). Previous work that compared the installed bandwidth potential with actual traffic flows found that "the average user only uses its promised full bandwidth for effectively nine minutes per day" (Hilbert & López, 2012a). Users might sit in front of a computer for hours, but the full bandwidth is on average only filled with traffic during a much smaller proportion.

Here we focus mainly on international comparisons, which makes it less relevant to ask if there is a flaw in the metric, but to ask if the flaw is different in different countries. For the purpose of international comparisons, both bandwidth potential and actual traffic would turn out equivalent if it were assumed that usage intensity within provided bandwidth would not differ among countries. This is of course not exactly true, as traffic prices, usage patterns and cultural habits differ among countries and can influence bandwidth usage intensity. However, the comparison aspect makes any systemic flaw of speed tests somewhat less worrisome.

2.2. Normalizing information time series

The creation of meaningful time series for bandwidth capacities hinges on temporal normalization on technological progress in compression algorithms. Advancements in lossless compression allow to send the same amount of information with less binary symbols (in the sense of Shannon, 1948). Compression is omnipresent in the digital age and is at the core of solutions like GSM, CMDA, JPEG, MPEG, etc. The amount of information transmitted through the same hardware channel has been significantly increased through the ever more sophisticated use of compression algorithms. Previous estimates have shown that content compression has contributed with a compound annual growth rate of over 10 % to the global growth of the effectively telecommunicated traffic between 1986 and 2007 (compared with a 8 % contribution of infrastructure expansion and additional 7 % though better hardware) (Hilbert, 2014a). This shows that compression is an important driver of the global information explosion.

Achievable compression rates vary significantly among different kinds of content, depending on the amount of redundancy in the source. For example, video content is usually more compressible than alphanumeric text. Therefore, the creation of the average compression rates at certain points in time requires two main inputs: the kind of content flowing through fixed and mobile network; and achievable compression rates for different kinds of content. We estimate the amount of content by distinguishing between text, images, audio and video, for fixed and mobile, upstream and downstream, according to five world regions (Sandvine, 2014; Cisco Systems, 2015). We estimate the corresponding average state of the art of compression rates per kind of content every seven years, for 1986, 1993, 2000, 2007 and 2014 and interpolate between them. This spacing gives enough room to identify the dominating compression technology at a given point in time (see Supporting Material). We also estimate the optimally achievable compression rate, which approximates the entropy of the source (Hilbert & López, 2012a).

We take advantage of the unique role of the entropy of the source (following Shannon's source coding theorem; Shannon, 1948) and use it as our anchor of normalization. We then normalize the content in time, acting as all content would always be optimally compressed. Since the entropy of the source is a constant and since today's compression algorithms have gotten quite close to it, this gives us a stable ground to stand on while evaluating the incessantly moving technological frontier in compression. The result is reminiscent of what economists do when normalizing on inflation rates. It allows us to create meaningful time series that quantify comparable amounts of information through time, not merely the quantity of more or less efficiently compressed binary symbols (Hilbert & López, 2012a). The resulting unit of measurement are optimally compressed bits, which we represent as kilobits per second (kbps) for telecommunication solutions.

This now finally provides us with our second main indicator: **installed bandwidth potential**, measured **in optimally compressed kbps**. This is our indicator for telecommunication capacity, which quantifies bandwidth. As with subscriptions, for reasons of simplicity, we will often work with the total sum of installed bandwidth potential, which does not mean that more fine-grained analysis would not be possible (see Figure 2b).

3. Results: bandwidth divides

Figure 2 visualizes the source of the discrepancies between the tradition accounting of subscriptions, versus the accounting of bandwidth potential measured in optimally compressed kbps. Both, the accounting of subscriptions (Figure 2a) and bandwidth capacity (2b) evidence the elimination of the dominance of fixed line telephony, which was the dominating form of distance communication in the late 1980s. In terms of the number of technological devices, this dominance was clearly replaced by mobile telephony, especially narrowband 2G and 2.5G phones, and in more recent years, broadband smart phones. However, in terms of telecommunication capacity, it shows that fixed-line broadband plays the dominant role. Representing less than 9 % of the world’s subscriptions, DSL, cable modem and fiber optics contribute 57 % to the global bandwidth potential in 2014.

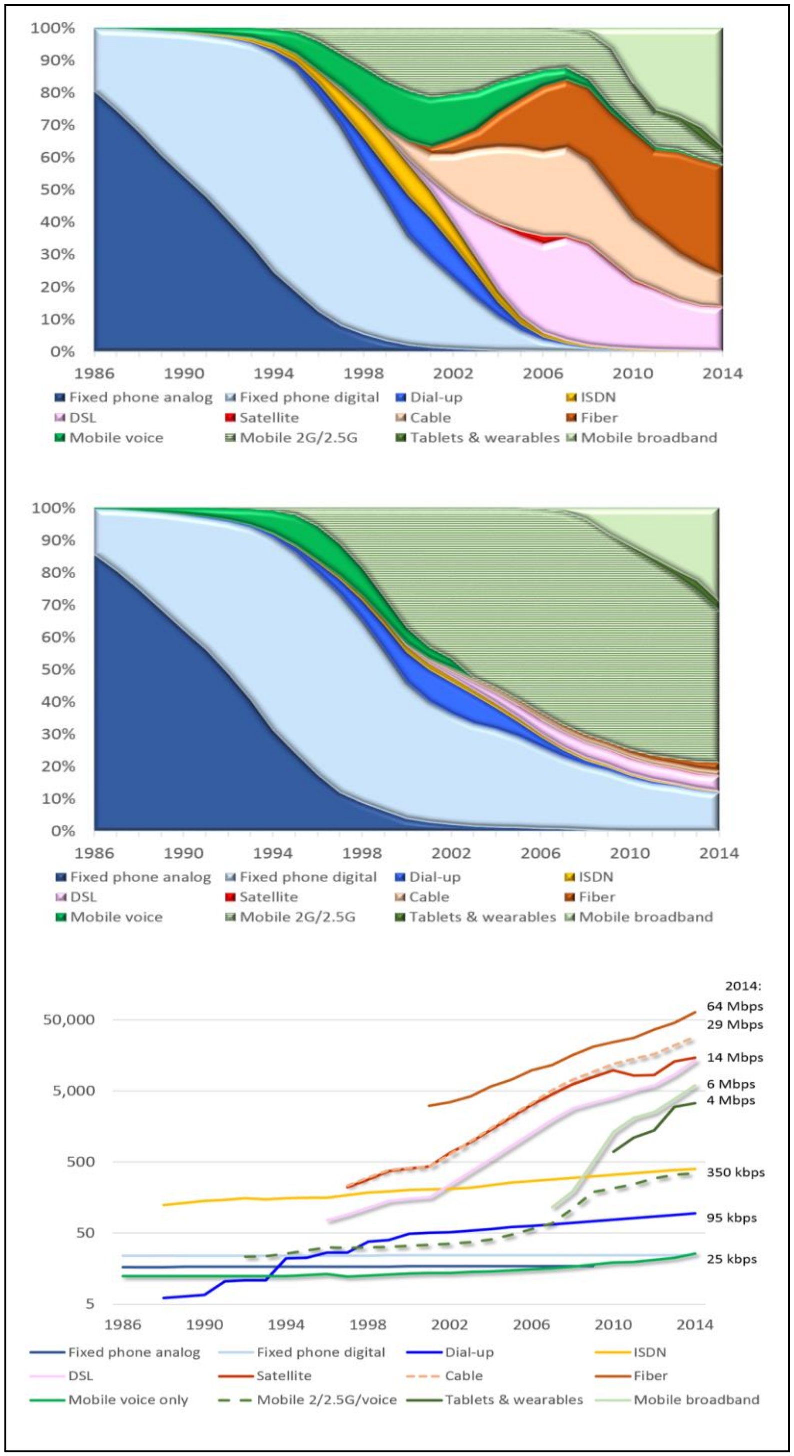


Figure 2. Global shares of technologies (upload+download; fixed&mobile; voice&data): (a) subscriptions, (b) installed bandwidth potential, (c) installed bandwidth potential per subscription

It is interesting to observe that the relation between subscriptions and bandwidth is neither linear, nor stable. For example, while we detect a monotonically[4] increasing share of mobile phone subscriptions (Figure 2a), the contribution of mobile to global bandwidth is continuously fluctuating with incessant technological innovation, reaching some 37 % in both 2001 and 2011-2014, while falling to 16 % in 2007 (Figure 2b). The increasing importance of mobile broadband in recent years is noticeable, representing 37 % of the installed bandwidth potential, while contributing 29 % of global subscriptions. In this case, it is the number of subscriptions that contribute mass to the total. The most recent contributions of tablets and wearables show the potential to once again shift the picture of the global telecommunication landscape in the short-term future. Figure 2c shows the corresponding bandwidth averages per subscription.

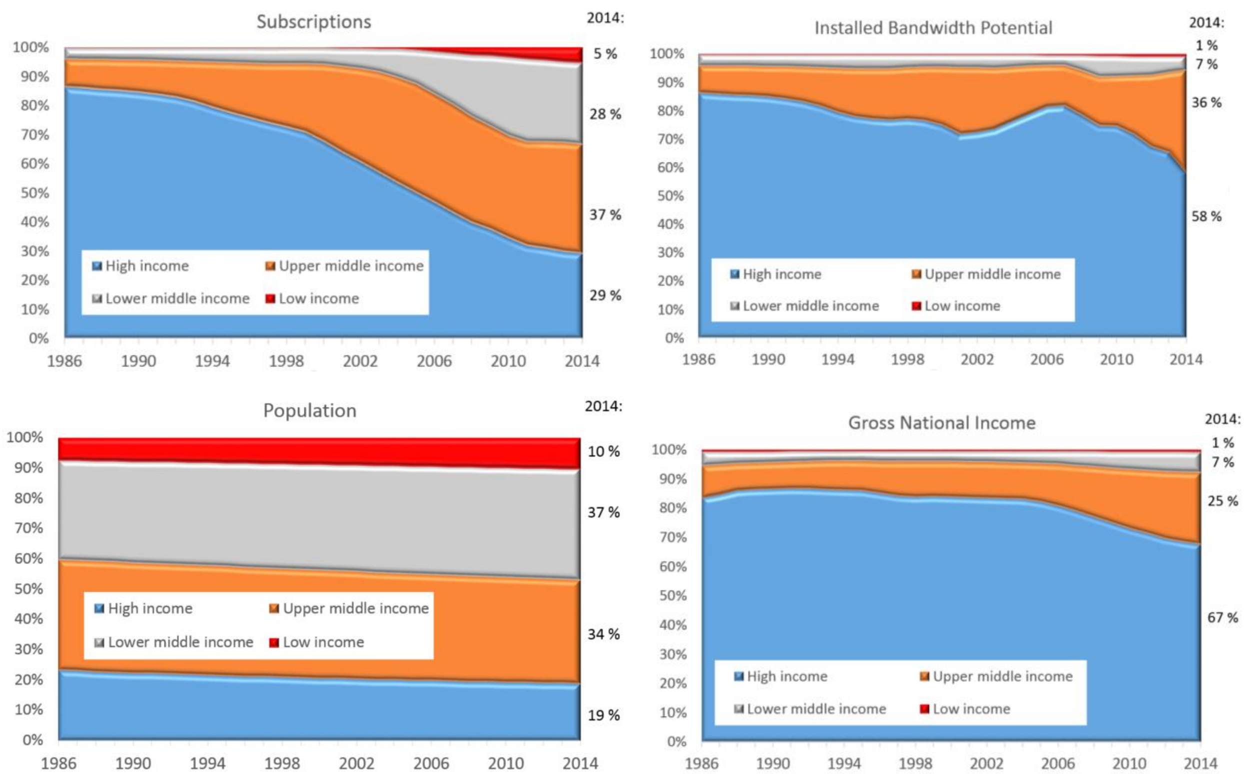
3.1. The divide between high- and low income regions

Figure 3 looks at the global total in terms of global income groups (following the classification of the World Bank (2015)). The last three decades show a gradual loss of dominance of today's high income countries. High income countries contributed some 85-86 % of the global subscriptions and installed bandwidth potential in 1986, but in 2013 merely 29 % of subscriptions (Figure 3a) and 58 % of bandwidth (Figure 3b). This also shows that global deconcentration in terms of subscriptions was twice as strong as in terms of bandwidth. Only four of the top-12 leading contributors to the worldwide stock of telecom subscriptions are high-income: China, India, *U.S.*, Indonesia, Brazil, *Russia, Japan, Germany*, Vietnam, Pakistan, Nigeria, and Mexico.

Comparing these results with the global shares of population and Gross National Income (GNI) (Figure 3c and 3d), it becomes clear that the diffusion dynamic of the number of subscriptions follows existing patterns in population distribution. Especially the diffusion of mobile phones during recent decades has contributed to the fact that both distributions have aligned in recent years. For example, upper middle income countries host 34 % of the world's population and 37 % of telecom subscriptions. On the contrary, bandwidth rather follows the signature of economic capacities (Figures 3b and 3d). For example, in 2014 lower middle income countries host 7 % of the world's GNI and 7 % of global bandwidth potential. In short, subscriptions follow populations, while bandwidth follows income. This is worrisome, since the income divide is notoriously persistent. This shows that the digital divide in terms of data capacity is far from being closed, but is rather becoming a structural characteristic of modern societies, which could turn out to be as persistent as the existing income divide [**Error! Bookmark not defined.**].

[4] Monotonicity describes a quantity that varies in such a way that it either never decreases or never increases.

Figure 3: Global income regions: (a) subscriptions, (b) installed bandwidth potential, (c) population, (d) Gross National Income (GNI) (in current USD).

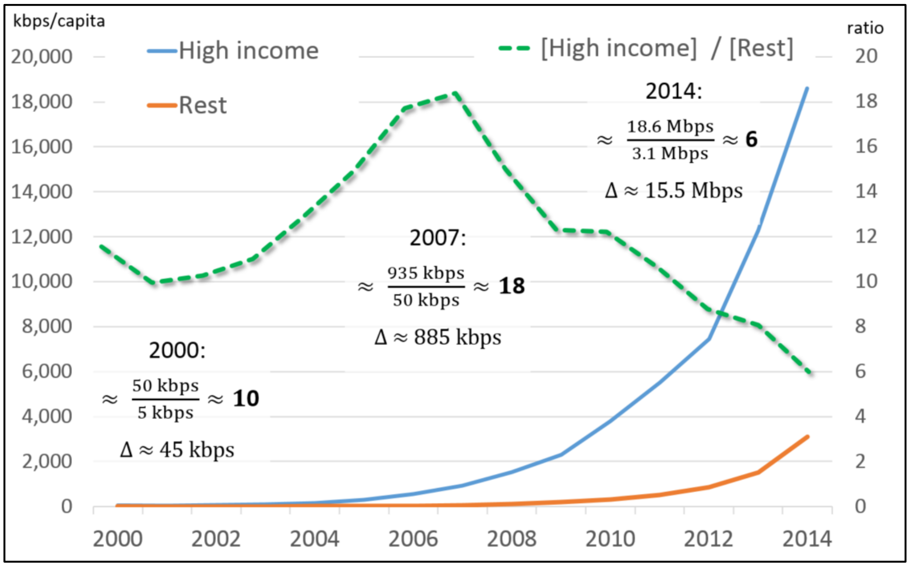


Another interesting insight from Fig 3b is that the evolution of bandwidth is also not monotonic among countries. High income countries controlled a dominating share of 82 % in both 1993 and 2007, but their share was at 72 % in 2001 and 2011.

This non-monotonicity[4] becomes even more evident when analyzing these tendencies as per capita ratios. Figure 4 shows that in 2000 high income countries had 10 times more bandwidth per capita than lower income countries, which increased to a gap of 18:1 in 2007, to fell to 6:1 in 2014. The reason for this in fluctuating tendency of the divide in terms of bandwidth capacities is technological change combined with recurring patterns of unequal dynamic of technology diffusion. The increasing nature of the divide between 2000 and 2007 is due to the global introduction of broadband for fixed and mobile solutions. The most recent decreasing nature of the divide is evidence of the global diffusion of broadband. Every new technological innovation has the potential to increase the divide once again, as every innovation once again runs through the process of technology diffusion through social networks (Hilbert, 2011), which is never neither instantaneous, nor uniform, and therefore inevitably creates a divide.

Figure 4 shows another very important fact. The divide continuously increases in absolute terms as technological progress increases bandwidth. In 2000, the average inhabitant of high income countries had access to an average of 50 kbps of installed bandwidth potential, while the average inhabitant of the rest of the world had access to merely 5 kbps. In absolute terms, this results in a difference of some 45 kbps. This divide increased with an order of magnitude every 5 years, reaching almost 900 kbps in 2007, and over 15,000 kbps by 2014. This increasing divide in absolute terms is important to notice in the context of a big data world, in which the amount of data is becoming a crucial ingredient for growth (Manyika et al., 2011; Hilbert, 2016).

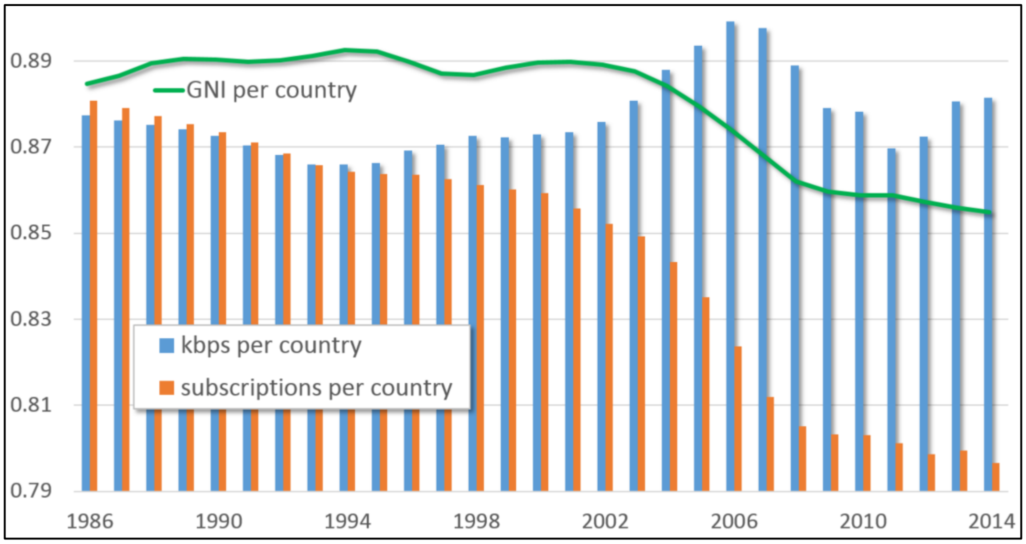
Figure 4: Bandwidth potential per capita; left-hand axis: avg. kbps per capita for high income countries and the rest of world; right-hand axis (dotted line): ratio of kbps/capita for high income countries divided by rest of world.



3.2. The divide among countries

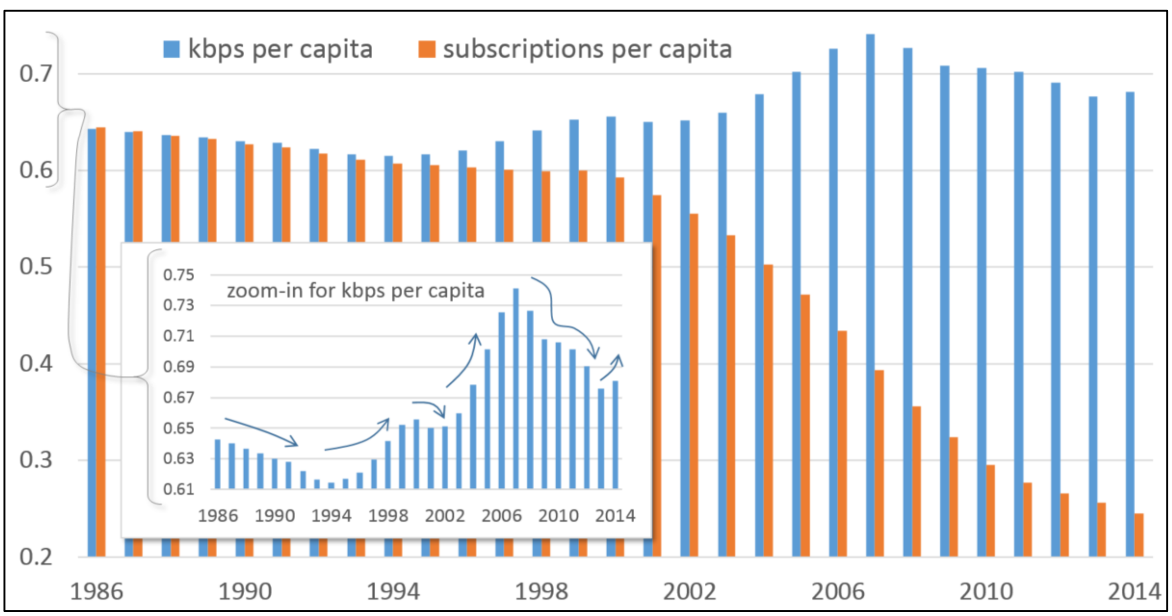
We now focus on the trajectory of the divide among all 172 countries in our sample. We can use the well-known Gini metric of inequality to obtain a single number (Gini, 1921). The Gini coefficient is normalized between 0 (maximal equality) and 1 (maximal inequality). Figure 5 shows the Gini coefficient for the number of subscriptions per country, the installed bandwidth capacity per country (in optimally compressed kbps) and, for reasons of comparison, the Gross National Income (GNI) per country. Once again, we see clear evidence for a closing digital access divide in terms of subscriptions. We also evidence a quite monotonic tendency in terms of more equally distributed global income among countries. The divide in terms of installed bandwidth capacity, however, does not follow a clear monotonic pattern. The Gini coefficient has been as low as 0.866 (in 1994) and as high as 0.899 (in 2006). Most recently, during 2011-2014, it has increased once again.

Figure 5: Gini coefficient among countries: installed bandwidth in kbps, subscriptions, GNI (current USD).



We can run the same analysis for the global inequality per capita. This means that we evaluate the trajectory of the number of subscriptions per capita and the installed kbps per capita. Figure 6 once again reveals a similarly monotonic pattern for the diffusion of devices, but a fluctuating pattern for bandwidth. As shown by the insert in Figure 6, there are just as many increasing as decreasing periods.

Figure 6: Gini coefficient for per capita metrics among countries: installed bandwidth in kbps, subscriptions.



Both Figures seem to suggest that a new process of concentration of bandwidth potential has started among countries. The reason is the rise of Asia. As shown in Figure 7, Asia share of global bandwidth potential increased from 1 in 4 bits of bandwidth around 1990, to more than 1 in 2 bits by 2014. With 54 %, Asia hosts more than half of globally installed bandwidth potential. Figure 7 shows that this leading role of Asian countries has undergone an internal change. In 2001, South Korea and Japan represented 16 % of global bandwidth potential, while Russia and China represented 15 %. By 2006, South Korea and Japan expanded its global share to 28 %, mainly driven by their early adoption of fiber optic broadband. Russia and China feel to 11 %. By 2014, the latter expanded their global share to 33 % (28% from China), while South Korea and Japan fell back to 16 %. This implies that together these four countries capture 49 % of the installed global bandwidth potential.

Figure 7: Installed bandwidth potential in kbps per geographic regions: the rise of Asia

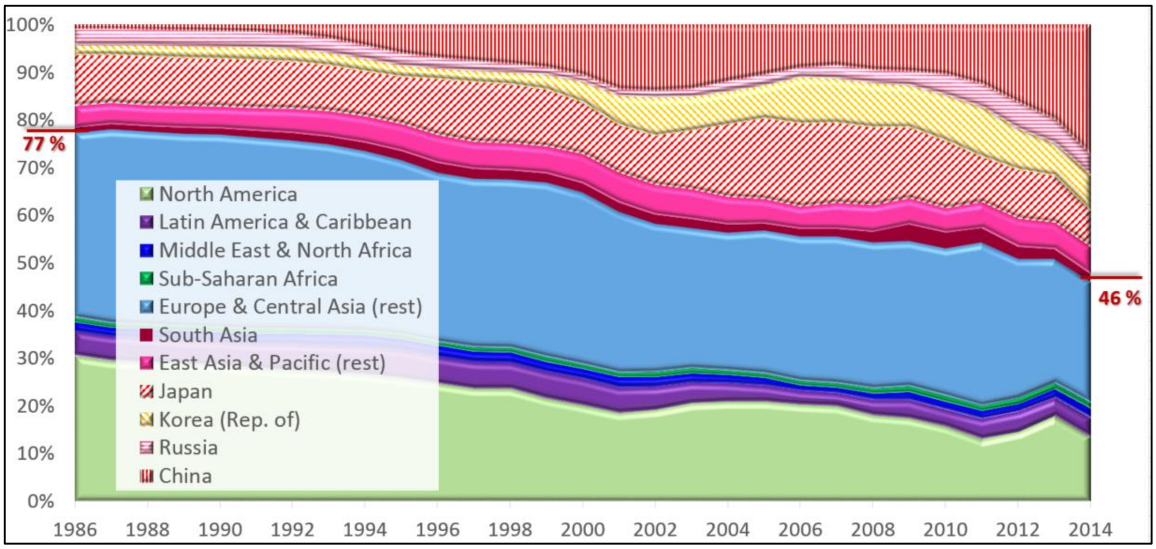
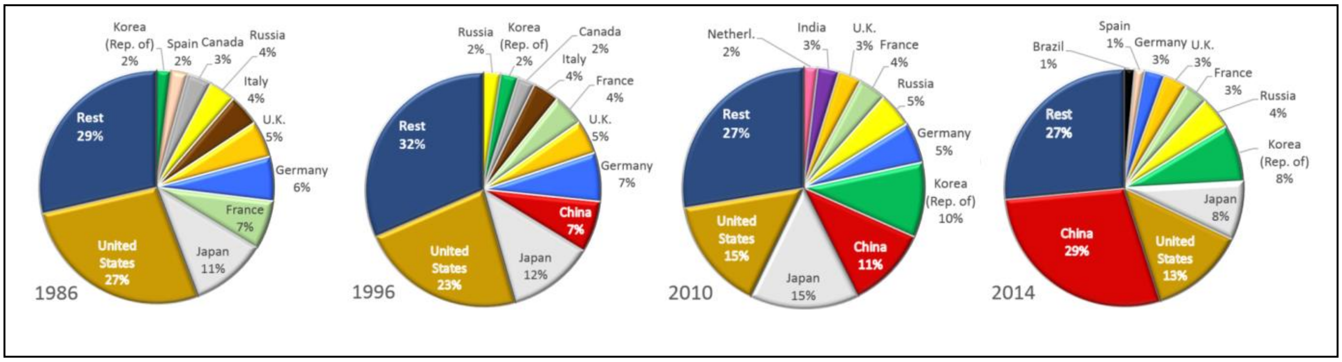


Figure 8 shows evidence that especially the last few years some important rearrangements with regard to which countries lead the pack in the global bandwidth race. Back in 1986, a group of traditionally highly developed countries were found in the global top ranks. The U.S., Japan, France and Germany hosted more than half of global bandwidth. By the second half of the 1990s, China had started to join the top ranks, hosting 7 % of global bandwidth in 1996. During the second half of the 2000s, three Asian countries, Japan, South Korea and China occupied ranks 2, 3 and 4. The share of global bandwidth of the U.S. had almost shrunk to half its size from the late '80s by 2010, representing less than 15 %. At the same time, Russia had regained its position as an important player in terms of telecommunication capacity. The years 2010 was also the last year in which the U.S. ranked number 1. Stating in 2011 China has taken the global lead in terms of installed bandwidth capacity, hosting some 1.30 Petabits per second, versus 1.26 in the U.S.. By 2014, China hosts almost twice as much bandwidth potential than the U.S..

It is interesting to notice that despite the profound reorganization within the ranking over the decades, the share of the top-10 countries has stayed surprisingly stable at 70 % of global bandwidth. This means that historically, a very small group of countries dominates global bandwidth. It is also interesting to notice that the top-3 countries usually captured a share of about 40 – 45 %, but expanded its influence to 50 % in recent years. In 2014, only three countries contribute the globally installed bandwidth potential for every second telecommunicated bit of information.

Figure 8: Top-10 of the installed bandwidth potential per country.



3.3. The divide among people

It would be very interesting to see how the bandwidth divide evolves among individuals. Although statistics on the individual ownership of ICT have significantly improved over the past decade (Katz & Rice, 2002; U.N. Partnership, 2008), there is still a significant lack of internationally harmonized statistics that include access to bandwidth. We are therefore forced to work with a model with certain assumption. Of course, "all models are wrong; the practical question is how wrong do they have to be to not be useful" (Box and Draper, 1987; p.74). We will work with a model that aims at striking a middle ground in possible biases, and it turns out that it detects an important recent turn in events, which suggests that it might be useful.

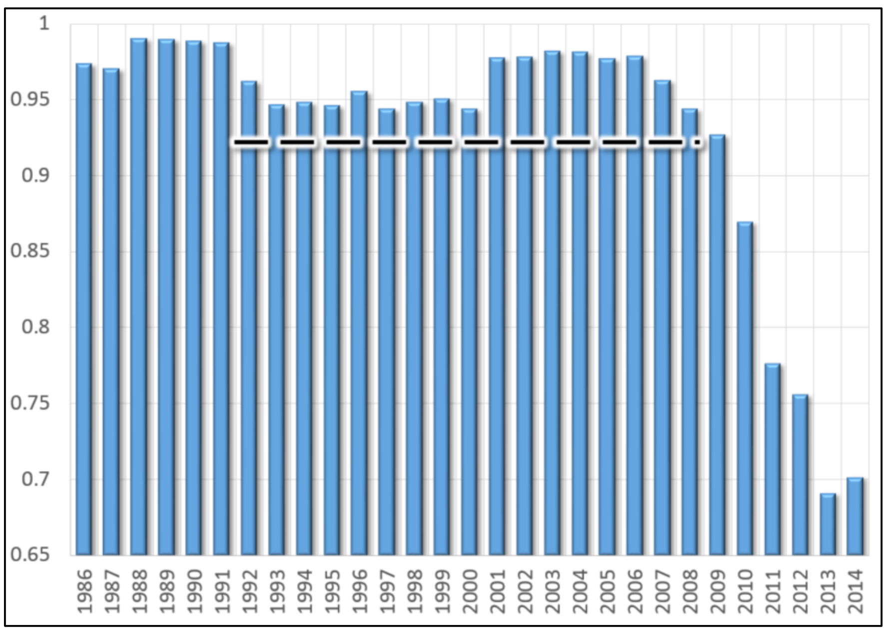
For this we create 'hypothetical users' and assign them different combinations of access solutions (Hilbert, 2014c). We assume that a person can maximally possess three different kinds of subscriptions (Internet, mobile phone, and fixed-line telephony[5]) and that the 'most connected group' of people possesses the highest performing subscriptions of all three kinds of technologies: the best available Internet subscription, the best available mobile phone, and a fixed-line phone. The second group of is defined as the group that has the next best performing set of subscriptions, which means that there are no more 'best subscriptions' of a certain kind available. It is replaced by the next highest performing subscription of the same kind subscriptions (Internet, mobile phone, or fixed phone), which defines the second group, and so forth. In other words, a group of users is defined by having the same three access solutions, and we stratify the entire population from a group with the best, down to a group with the least powerful access solutions worldwide. Users from the lower end can also own only two subscriptions, or one, or none at all.

[5] We distinguish between two kinds of fixed phones: fixed phone analog & fixed phone digital; six kinds of Internet subscriptions: dial-up, ISDN, DSL, satellite, cable modem, FTTH/B; and four kinds of mobile access solutions: mobile voice only, mobile 2G/2.5G, tablets & wearables, mobile broadband.

The methodology behind this indicator is subject to two main biases. On the one hand, it can be biased toward more concentration than actually exists. In reality one person might possess only a mobile phone and no fixed phone; or a high-bandwidth internet connection but a low-bandwidth mobile phone, and so on. In this case, our assumption overestimates true inequality, as we force the highly connected to have the best of all three kinds. This bias increases in later years with the diversity of existing devices (the bias did not exist in the late 1980s at the time of exclusivity of uniformly performing fixed-line phones). On the other hand, it can be biased into the other direction toward less inequality than actually exists. In reality some users might possess multiple mobile phones, and have multiple internet subscriptions, etc. In this case, our assumption underestimates true inequality. Without further data on a global scale, we expect both biases to counteract on each other.

Figure 9 once again uses the Gini coefficient to analyze the distribution of installed bandwidth capacity among the resulting groups. It shows that bandwidth potential inequality fluctuated during the 1990s and 2000s, increasing and decreasing as a result of the interplay between technological innovation and diffusion. The good news is that recently, during the five years from 2009 – 2014, the digital divide among individuals in terms of bandwidth has finally started to decrease notably. The main driver of this fact is the global diffusion of fixed and mobile broadband, and a somewhat decelerating tendency of technological change (see the performance of mobile broadband and cable modem in Figure 1c since 2009). At the same time, we can once again notice a slight increase in inequality between 2013 and 2014. Considering the methodological limitations of the data, this might not necessarily mean much, but it warns us not to be overly hasty when extrapolating such tendencies for medium- and long-term projections.[6]

Figure 9: Gini coefficients for the distribution of installed bandwidth potential among 'hypothetical users' for individuals worldwide.



[6] Note that the chosen methodology here assumes an individual to accumulate up to 3 devices. This happens to result in the fact that there are about 7 billion users out of 7 billion people worldwide (using some 9 billion subscriptions). This implies some kind of breaking point in 2014 (following our assumption). In the future, the so-called internet of things (Atzori et al., 2010) and wearables could make it questionable to restrict the number of devices per person to 3. This could lead to a different result with regard to accumulation of devices among the worlds most highly connected.

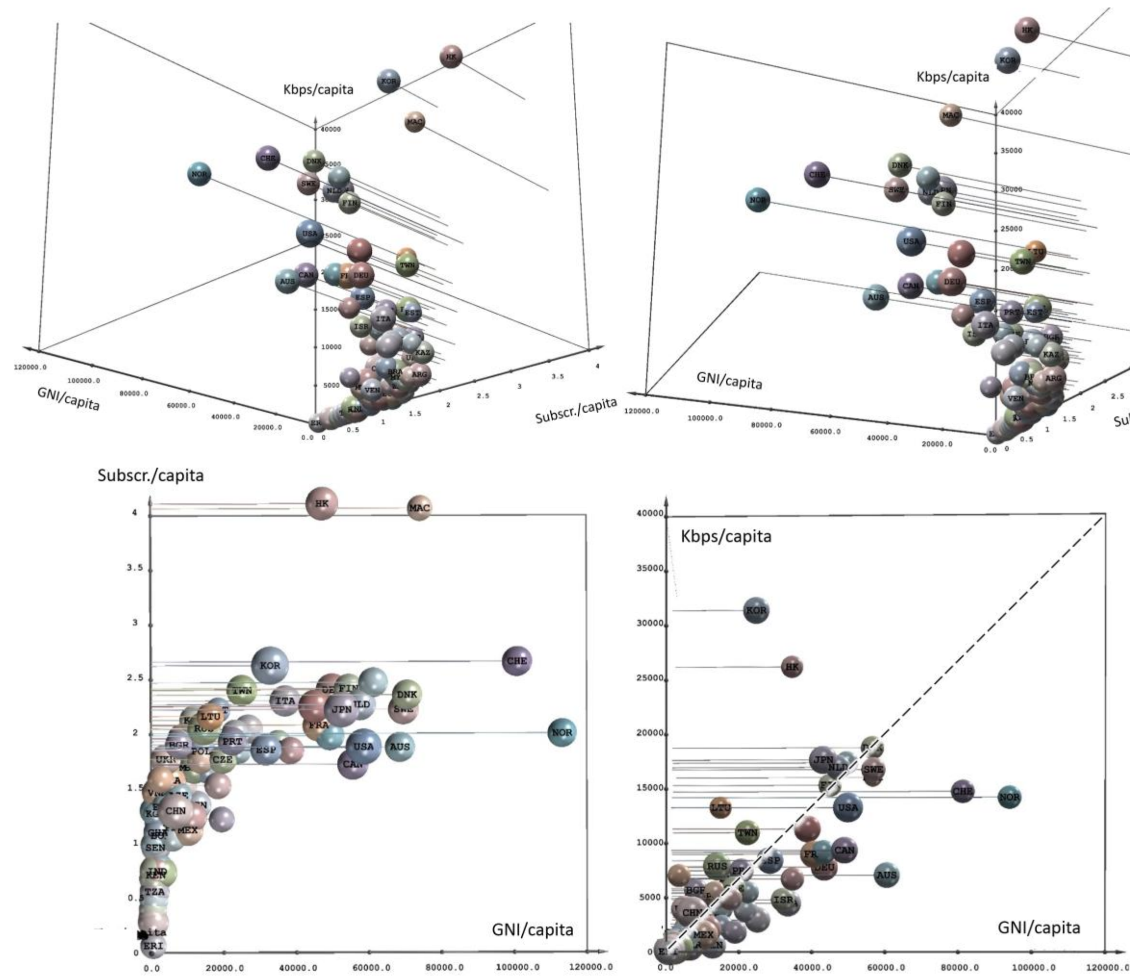
Why do we see this important drop on a global level, while the analysis among countries in Figures 4, 5 and 6 merely shows continuous fluctuations? Why the crude approach that leads to Fig. 9 cannot tell us much details, part of the reason is certainly revealed by the changing global ranking in Fig. 8. The rise of the world's most populous country (i.e. China) leads to the fact that many more people worldwide have access to more bandwidth. Fig. 3b and 3c reveal that there is much room in this direction: globally installed bandwidth is by far not distributed in agreement with global population levels, but it shows that upper middle income countries have caught up significantly during reent years. This discrepancy between the international and individual levles underlines the significance of the lack of insight on the level of the individual, and emphazises the urgency to collect such metrics.

3.4. Trajectories of bandwidth diffusion

Last but not least, let us look at the evolution of the divide country level from a multidimensional perspective. Figure 10 adds the dimension of income per capita (GNI per capita) on a third axis of Figure 1b. It suggests that countries move along the axis of subscriptions per capita quite independently of their income level. Rich and poor countries alike are found with up to 1.5 -2 subscriptions per capita. After having reached about 2 subscriptions per capita (roughly one fixed and one mobile solution), saturation sets in, regardless of income. However, the digital divide continues to evolve. In contrary to Figure 10c, no non-linear L-shaped saturation logic can be detected when analyzing the relationship between kbps/capita and GNI/capita in Figure 10d. The relationship rather follows the trajectory of a diagonal linear one-to-one relationship between bandwidth and income. This reconfirms the previous finding that the digital bandwidth divide goes hand in hand with income, and therefore has the potential to become as persistent as the income divide.

Of course, the insinuated correlations do not imply causation. However, some leads can be obtained from interesting outliers detectable in Figure 10. Countries like Switzerland (CHE), Norway (NOR) and Australia (AUS) have less bandwidth potential than their income level would suggest. The U.S. (USA), Canada (CAN), France (FRA) and Germany (DEU) also fall in this underperforming category. Others, like South Korea (KOR), Hong Kong (HK), Japan (JPN), Lithuania (LTU), Russia (RUS) and China (CHN) have more installed bandwidth that is to be expected with regard to their income. South Korea, Japan and Lithuania has long been identified as global best practices of government-led broadband role out (Kantei, 2001; Rhee & Kim, 2004; Government of Lithuania, 2005. This leads to questions on how much bandwidth development might be influenced through pro-active public policy.

Figure 10: Different perspectives on three dimensions of the digital divide: subscriptions per capita; kbps per capita; GNI per capita. N = 100 countries for 2013. Size of bubbles: log population.



4. Conclusions

During the discussions about the right choice of indicators to monitor the United Nations Sustainable Development Goals (SDGs) in 2015 (the "post-Millennium-Development-Goals"), two digital divide access indicators were discussed. The indicator "subscription to mobile cellular and/or fixed broad band internet" was evaluated as "feasible, suitable and very relevant (rating AAA)", while the indicator "fixed and mobile broadband quality measured by mean download speed" was evaluated as "only feasible with strong effort, in need for further discussion and somewhat relevant" (UNSC, 2015). This article has shown that this "strong effort" will be inevitable, as measuring bandwidth quality has become very relevant already. This is because both technology diffusion and technological progress is rendering the number of subscriptions increasingly obsolete and meaningless as the stand-alone main indicator. While the digital divide in terms of subscriptions is rapidly closing, the digital divide in terms of bandwidth is rapidly evolving and here to stay. The article has shown that the digital divide in terms of bandwidth is actively evolving and showing lots of dynamics on the international level during recent years.

The result is an ongoing divide as the result of an intricate interplay between continuous technological progress and recurrent processes of technological diffusion. Each technological innovation is associated with a new diffusion process. The divide will continue as long as technological progress continues. Economist refer to this process as "red queen effect", which refers to a dynamic in which standing still means falling behind (it refers to the Red Queen in Alice's Wonderland, who explains that one has to constantly run to simply stay in the same place). Technological progress in terms of bandwidth does not show any signs of slowing down. Once everybody is equipped with top-notch smartphones and fiber-optic connections, which is the technological frontier in 2014, others will have holograms and brain-computer-interfaces, or some other kind of yet unpredictable product of the ceaseless creative destruction of technological innovation.

This leads to many open questions on the research agenda. As stated at the outset, the idea behind this article is to showcase an argument, not to provide all-embracing solutions. One open challenge refers to the multiple causations and implications of bandwidth differentials. In this article we have frequently look at the relation to income levels. Income is traditionally the most pervasive indicator of development, which justifies this choice for a first exploration. We have seen that bandwidth potential is closely linked to income levels, and might therefore be subject to a similar persistency as global income inequality. At the same time the presented data has also aimed at clarifying the persistent claim that cost in telecom are falling so quick that economic wealth always becomes less of a factor. This argument has been made during the 1990s for narrowband internet, during the 2000s for mobile telephony, and during recent years for broadband. Several figures (including Fig. 3, Fig. 8, and Fig. 10) have shown that this argument does not hold on the international level. We cannot find evidence for this argument among countries. While this leads to important new discussions, income is not the only decisive factor. We have also seen deviations from the correlation with income. Analysis like the one in Fig. 10 can be done with many other additional indicators that give us a better understanding of the evolution of bandwidth.

Another challenge refers to the generative mechanism of the detected "red queen" dynamic. The ensuing interplay between continuous progress and diffusion cycles is complex and affected by many factors. For some cases it has been shown that the resulting distribution among technological devices and their performance follows a power-law that arises as an interplay between exponential technological progress and exponential social diffusion (Hilbert, 2014b). Power-laws (or Pareto-distributions) are extremely skewed distributions, where exponentially few have exponentially much, and exponentially many, have exponentially little. In cases where this occurs, the divide follows a very predictable pattern: it is predictably and persistently extremely unequal.

Last but not least, as stated in the outset, the speed-test metric used here has many flaws and limitations. We chose it because it provided a readily available way of assessing bandwidth. Using crowd-sourced speedtests as a source gives good first idea, but is surely not perfect. Differences in testing behavior, biases with regard to the proportion of testing of different technologies, and national market structures all affect the result. Discussions about a more reliable way of systematically collect bandwidth data have to be intensified. Besides, bandwidth has two main dimensions to it: the installed capacity (much in the sense measured here) and effective traffic (the fraction of bandwidth effectively used) (Hilbert & López, 2012b). The first is a general condition sine qua non (measured here), while the second allows to detect differences in terms of efficiency and effectiveness of infrastructure supply and demand.

There are other, additional metrics that can be used to complement these two fundamental indicators. One still refers to subscriptions. While the traditional reliance on the number of subscriptions as main digital divide indicator has been the main subject of critique throughout this article, it still provides important insights. Without subscriptions, no bandwidth, and for some applications, bandwidth might also be less relevant than for others: the end justifies the (measurement) means (Hilbert, 2011). Technological progress toward the so-called internet of things (Atzori et al., 2010) might also once again increase the relevance of the number of subscriptions as indicator. Besides, Vicente & Gil-de-Bernabé (2010), for example, have added network latency as part of their broadband quality score. Following the argument of going beyond access and looking at usage patterns (van Dijk, 2005), others have started to complement broadband data with data about social media usage (Pick et al., 2015) and user skills (Lee et al., 2015). Just like the first subscription-driven stage of the digital divide was filled with very different and sometimes contradicting proposals for adequate ways of measuring ICT access (Minges, 2005), the second bandwidth-driven stage of the digital divide will still have to find an adequate way of measurement. Future research will have to reveal which aspects matter most (and for what). As in the past, this will include coarse-grained composite indexes (e.g. Minges, 2005), as well as fine-tuned application specific definitions of future outlooks on the digital divide (Hilbert, 2011). It was the goal of this article to contribute to the continuous evolution of the definition of the digital divide.

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