Improving content delivery in low-resource networks: a case study of the African Internet Ecosystem

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Improving content delivery in low-resource networks: a case study of the African Internet Ecosystem

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Declaration of Authorship

I, Amreesh Dev Phokeer, declare that this thesis titled, “Improving content delivery in low-resource networks: a case study of the African Internet Ecosystem” is my own original work. Where collaborations with other researchers are involved, or materials generated by other researchers are included, the parties and/or materials are acknowledged or are explicitly referenced as appropriate.

This work is being submitted for the degree of Doctor of Philosophy in Computer Science at the University of Cape Town, South Africa. This thesis has not been submitted to any other university or institution for any other degree or examination.

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Publications

Some content in this dissertation have previously appeared in the following publications:

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- **Phokeer, A.**, Chavula, J., Johnson, D., Densmore, M., Tyson, G., Sathiaseelan, A. and Feamster, N., 2019, January. On the potential of Google AMP to promote local content in developing regions. In 2019 11th International Conference on Communication Systems & Networks (COMSNETS) (pp. 80-87). IEEE. https://doi.org/10.1109/COMSNETS.2019.8711393
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This thesis is dedicated to
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who have raised me to be the person I am today.

Om Namah Shivay

"The web has added a new dimension to the gap between the first world and the developing world. We have to start talking about a human right to connect." – *Sir Tim Berners-Lee*

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Abstract

The Internet is one of the most successful inventions of recent times. The COVID-19 pandemic has, once again, proven the importance of the Internet to society, and this has further demonstrated how critical it is to build networks that are resilient, accessible and inclusive. However, the Internet in many African countries is still limited by both technical and regulatory challenges. It is along these lines that this thesis proposes a series of studies, supported by empirical evidence, to better understand the challenges of content delivery in African networks.

The thesis starts by providing an understanding how the Internet is being used and consumed by low-income mobile Internet users in South African townships. By means of a mixed-methods study, combining quantitative network measurements with qualitative survey data, the thesis provides some useful insights about Internet usage patterns and the underlying reasons for specific user behaviour with regards to mobile data management. The research revealed how Internet usage patterns of users in low-resource settings are restrained by the lack of access, availability of services and data cost.It also reinforced the concept of *locality of interest* and at the same time showing that the mainstream Internet services remain very popular.

Next, the thesis investigates the impediments faced by African users to access local content and cloud-based services. This is achieved through a study on web content hosting, focusing specifically on African local news and public sector websites. It was found that 85% of local news websites are hosted outside their respective countries by foreign companies, mostly in Europe and in the US. This section revealed how a majority of Africa's local content is still hosted remotely and this has a major incident on the Quality of Experience (QoE) of users in Africa.

Considering the set of challenges of content delivery in Africa, companies such as Facebook and Google have introduced alternative mechanisms to

deliver content to the end-user - purportedly using bandwidth-friendly and cost-effective technologies. This thesis performs an in-depth Quality of Service (QoS) analysis of: (1) Free Basics, a “zero-rated” service from Facebook and (2) Accelerated Mobile Pages (AMP), a mobile optimisation technology by Google. The aim of both Free Basics and AMP is to reduce the cost of access and improve the QoE on mobile devices through different techniques - albeit with some caveats pertaining to net neutrality and data privacy. However, the thesis reveals that Free Basics services provide weaker network performance than their paid counterparts, which contributes to a disjointed user experience. On the other hand, Google AMP pages can reduce traditional page sizes by a factor of 8 and the results show that Page Load Time (PLT) on African networks can significantly be improved. However, both Free Basics and Google AMP introduce serious concerns with regards to net neutrality and data privacy.

One way to minimise the effects of cross-continental path is to host the content as close as possible to the end-users. For this, there must exist a robust interconnection ecosystem between African networks. The thesis performs a deep-dive in both intra-country and inter-country connectivity in Africa, looking into both delays and network path by means of a longitudinal active measurement study. The latter exposes interesting topological characteristics of cross-border connectivity and provides evidence on the existence of circuitous routing and a lack of peering within African networks. The thesis reveals a series of “communities”, in which countries have built up low-delay interconnectivity, dispelling the myth that intra-delays in Africa are universally poor.

Finally and taking into account the above, the thesis studies how the development of localised Internet infrastructure such as Internet Exchange Points (IXPs) and Data Centres (DCs) can help democratise access to local content. Using a simple multi-level maturity model, the thesis categorises the readiness of African countries to provide a *localised Internet infrastructure*. The thesis further explores the above hypothesis by estimating the effect of *increasing the number of participants of an IXP* on the *local content activity* of the country. The latter was achieved by using a fixed-effects econometric model and a positive correlation was found between the *scale of an IXP* and the *local content activity*. The thesis finally provides some key policy points on how to improve content delivery in African networks.

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Acronyms

A4AI Alliance for Affordable Internet.

ADSL Asymmetric Digital Subscriber Line.

AMP Accelerated Mobile Pages.

API Application Programming Interface.

AS Autonomous System.

ASN Autonomous System Number.

CAPEX Capital Expenditure.

ccTLD Country-code Top-Level Domain.

CDF Cumulative Distribution Function.

CDN Content Delivery Network.

CMS Content Management System.

CN Community Network.

CP Content Provider.

DC Data Centre.

DDoS Distributed Denial of Service.

DNS Domain Name System.

DNSLT DNS Lookup Time.

FTTH Fibre to the Home.

GDP Gross Domestic Product.

GNI Gross National Income.

GSMA GSM Association.

HHI Herfindahl-Hirschman Index.

ICMP Internet Control Message Protocol.

ICT Information and Communication Technology.

IETF Internet Engineering Task Force.

IP Internet Protocol address.

ISOC Internet Society.

ISP Internet Service Provider.

ITU International Telecommunication Union.

IXP Internet Exchange Point.

LDC Least Developed Country.

LLDC Landlocked Developing Country.

Mbps Megabit per second.

MENA Middle East and North Africa.

MMLPA Mandatory Multilateral Peering Agreement.

NSRC Network Startup Resource Center.

OTT Over-the-top.

PLT Page Load Time.

PoP Point of Presence.

QoE Quality of Experience.

QoS Quality of Service.

ROI Return on Investment.

RTT Round-Trip Time.

SSL Secure Sockets Layer.

SSLNT SSL Negotiation Time.

Tbps Terabit per second.

TCP Transmission Control Protocol.

TEI Total Economic Impact.

TLS Transport Layer Security.

TTFB Time to First Byte.

UDP User Datagram Protocol.

UN United Nations.

VOIP Voice Over IP.

W3C World Wide Web Consortium.

WISP Wireless Internet Service Provider.

Chapter 1

Introduction

It is without any doubt today that the adoption of Information and Communication Technologies (ICTs) particularly broadband Internet and mobile connectivity is an important tool for economic growth and development. The United Nations (UN) has in fact, through the Sustainable Development Goal 9.c, set a target to "Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in the Least Developed Countries (LDCs) by 2020"[1].

Africa is home to 33 LDCs out of 47 countries with the lowest indicators of economic development. Out of which, there are 16 Landlocked Developing Countries (LLDCs) such as Burundi, Chad or Niger with the least Internet penetration rates on the continent (5.6%, 6.5% and 10.2% respectively). One contributing factor is high transit costs due to the lack of cross-border connectivity, as reported in the Internet Society 2018 report on landlocked developing economies[2].

By contributing to the emergence of an information and innovation culture in key sectors such as trade, agriculture, financial services, transportation and government services, the Internet has helped to improve the livelihood of people in many dimensions. Many previous research studies have shown a strong correlation between increased investment in telecommunication and economic development [3, 4]. A recent study by Hjort *et al.* showed how the arrival of fast Internet in 12 African countries had had a positive impact on employment rates [5].

While significant progress has been achieved in the last ten years, Africa remains a land of major contrast. Internet users in major cities, in more advanced economies, benefit from a well-provisioned Internet ecosystem, yet, around 60% of Africa's population remains unconnected as of 2020 (ITU estimates). A phenomenon usually termed as the "Digital Divide". Table 1.1 gives a detailed overview of Internet penetration in Africa and how it evolved over the years.

Generally, the gap in Internet penetration between African countries can be linked to several factors namely **accessibility** to reliable and high-speed broadband network, **affordability**, **appropriate skills** and the **lack of relevant content** - as defined by the World Economic Forum in their "Internet for all" initiative [6]. Even if there have been great strides in the deployment of cable infrastructure (backbone and last mile) around the continent, the development has not been inclusive. For example, it is accounted that more than 50% of people living in remote and sparsely populated areas are still not covered adequately by a mobile broadband network - let alone high-speed broadband, 90% of the population in Africa "would be not be connected" as of 2018 if a 10 Mbps connection baseline is used. [7]

Furthermore, the issue of affordability is considered as a major obstacle preventing the wide-scale usage of the Internet. A report from the Alliance for Affordable Internet (A4AI) mentions that 1 GB of prepaid mobile data would represent around 10% of the monthly income of a mobile user in Africa [8], which is five times higher than the recommended threshold of 2% of monthly income per capita [7]. Prior studies have suggested that limited availability, accessibility and affordability of the underlying Internet technology is a key hindrance to the adoption of Internet services such as cloud computing in developing countries [9, 10]. There are many factors that can affect affordability such as lack of competition, proper national broadband policies or geography[1].

Internet in Africa, therefore, remains a luxury for a vast majority of people, a situation which tends to maintain the so-called "digital divide" and prevents unleashing the full potential that comes with unlimited/high-speed access to broadband Internet. The COVID-19 pandemic has undoubtedly accentuated this divide as people in low-income communities in both rural areas and urban areas still lack reliable and affordable Internet access and cannot embrace the digital transformation the world went through as a result of this global crisis.

Besides the issue of access to infrastructure and affordability, lies the overall quality of the Internet, an important element to consider with regards to "Universal access and usage". As per the statistics reported by the Worldwide Speed League, several countries have an average speed of less than 1 Mbps[11]. For example to download a high-definition movie (7.5GB), it would take more than a day in the three worst-ranked African countries (DR Congo, Burkina Faso and Gabon), while it would take

[1] It is interesting to note that countries with the least Internet penetration rate are usually the LLDCs such as Burundi (5.6%), Chad (6.5%) or Niger (10.2%). LLDCs usually suffers from a lack of cross-border connectivity and consequently from high transit costs as reported in the Internet Society 2018 report on landlocked developing economies[2].

two hours in Kenya, the highest-ranked country in Africa. Most of the time, the content being consumed by the users are not even hosted in Africa, negatively impacting the overall user experience. Several studies and reports have highlighted the issue of high latency and bad QoE in Africa [12, 13, 14, 15], including a recent report from A4AI [16].

In sum, while progress is real and happening, there are many aspects of the African Internet which can be improved for a more sustainable development. This thesis investigates to what extent the African Internet ecosystem is conducive to promoting the development of local (and relevant content) taking into account the problem of affordability.

1.1 Problem statement

The 2019 CISCO VNI report forecast that the average Internet traffic in Africa would increase 6.2-fold and would reach 46 Tbps by 2021 (and up to 222 Tbps in peak hours). The forecast actually changed with the arrival of COVID-19 pandemic in 2020, the global traffic increase by 47% in an unprecedented way [17]. As it has been observed, a big chunk of this traffic comes from Over-the-top (OTT) services such as e-commerce, social media and increasingly from online video streaming and video conferencing tools. To reduce latency and increase reliability, web traffic nowadays is mostly served by Content Delivery Networks (CDNs), with edge servers residing in well-provisioned DCs, geographically located on large Internet Service Providers (ISPs)' networks - or at IXPs - and closer to *eyeball* networks. Over the years, CDNs have proved to be an important component in the content delivery chain by reducing page load times, offloading traffic costs, balancing traffic spikes and caching content closer to the end users.

But are Internet users in Africa actually benefiting from the advantages of hosting content on locally (or regionally) hosted CDNs? Current reports are showing that CDN nodes and content caches are sparsely present on the continent, especially in Sub-Saharan Africa [18, 19, 20]. So, despite the increase in performance that CDNs provide to mainstream Internet users, a vast majority of the African population still suffer from low quality and high delay access to content. Additionally, the situation in Africa is often sub-optimal and costly, where more than 80% of traffic goes outside Africa, especially to Europe - namely due to a lack of hosting facilities and a lack of peering between networks in Africa [13, 21, 22, 12]. CDN operators often find it difficult to maintain their caches in an ecosystem which is expensive (in terms of bandwidth) and under-provisioned (in terms on reachability to eyeball networks). Some content providers, such as Netflix, prefer to run their own content delivery platform by deploying their edge nodes directly in the ISP network or at well-connected IXPs.

Furthermore, the peering ecosystem is also nascent in many African countries, leaving patches of connectivity in some regions, while some other parts of the continent enjoy high capacity backbone and access networks. Therefore, to be able to respond to the increasing demand of Internet users, Content Providers (CPs), ISPs and CDN operators need to understand the challenges undermining efficient content hosting and delivery on the continent.

1.2 Research questions and methodology

The main aim of the research is to consider *"what are the content delivery and performance bottlenecks in low-resource networks and how can access to local content be improved"*. This thesis attempts to address the above objective through five research questions: first by characterising Internet usage in low-resource networks; second by uncovering the challenges with content hosting and distribution; third, by evaluating alternative means of content delivery, especially those targeting the developing regions; fourth by running an Africa-wide analysis of country-level latencies and finally by estimating the effects of localised Internet infrastructure on local content hosting and distribution at a country-level.

1.2.1 Characterising Internet usage in low-resource networks

Research Question 1

What are the Internet usage patterns of users living in a low-resource environment?

The key objective of this first step is to understand how the Internet is being used and consumed by low-income users in an under-served environment. The research was carried out in a township area, close to Cape Town, South Africa. At first, users in this area did not have access to a public Wi-Fi and, therefore, they had to rely solely on their mobile connectivity. Internet usage was predominantly mobile and, therefore, quite restrictive. After a couple of months, a subsidised Wi-Fi network, called *iNethi*, was placed at the local school, which allowed students, teachers and members of the local community to connect to a range of localised services and to the Internet, using a voucher system. The *iNethi* network provided either free or very affordable connectivity to the Internet, therefore breaking down the barriers to access. It was important for this research to properly understand Internet usage patterns of a low-resource setting, moreso in an "untethered" fashion.

To achieve the above, a mixed-method study with passive network measurements and semi-structured interviews were employed. First, a mobile Internet usage campaign was designed and Internet users were selected from the community. Then, using the Myspeedtest application, Internet usage data were collected passively, whenever users were accessing any online service. Data captured on the mobile phones were sent to a central server, then aggregated to obtain the results for this study. Data was anonymised for privacy purposes. Then, semi-structured interviews were then carried out to extract qualitative information about mobile Internet usage.

Furthermore, a traffic characterisation study was performed on data collected on a proxy server which was deployed on the community wireless network, *iNethi*. Any service accessed on the local network or on the Internet, during the last six months, were passively captured in the form of packet capture (pcap) files. The data was then cleaned, processed and aggregated.

1.2.2 Understanding content hosting and distribution challenges in Africa

Research Question 2

Where is Africa's local content currently hosted and what is the impact on QoS for African users?

To answer this research question, two separate studies were carried out on the location and distribution of Africa's local content as well as the associated performance characteristics. Local content refers to content which is user-created, business-created, or government-created, it is intended to draw local readership and promote local language and culture [23]. Drawing from existing literature and surveys, specific behaviour patterns with regards to Internet access were identified. For example, on which platforms or websites users tend to spend more time, the limitations users are facing, etc. In addition to the above a quantitative study was run to where determine specific characteristics of local content such the location, ease of access and performance. For the latter, the study focused on a sample set of 1,095 African news websites, which was used as a proxy for local content.

In the same vein, another dataset of local content was explored, namely public service websites. E-Government websites and services are important indicators of local content activity. As such, it was important to know in which networks and countries are the public sector websites currently being hosted and whether or not this has an impact on the QoE perceived by the end-users. To get these answers, an Internet measurement study, using the RIPE Atlas measurement platform (see section 2.3.1), was performed to collect latency information.

1.2.3 Alternative means of content delivery

Research Question 3

What are the alternative content delivery mechanisms and what is their performance benefits with regards to QoS and QoE as perceived by end-users in Africa?

In the last few years, there have been several attempts to "bridge the digital divide" by facilitating content delivery to the end-users especially those living in bandwidth-constrained environments. In this thesis, two of the most widely deployed alternative content delivery mechanisms are studied and their performance benefits analysed.

The first proposal is the Free Basics initiative from Facebook. It is a "zero-rated" application which allows users to browse through a limited number of websites for free. Free Basics is currently available in a few countries including South Africa and Pakistan. This thesis performs a QoS analysis by running a measurement study. It first gathered data on the set of Free Basics web services, the web pages of these services to evaluate the functionality they offer and the network performance while downloading them and then compared the QoS of a Free Basics service with the QoS of the normal version.

The second proposal evaluated is the AMP project by Google. The performance of websites is defined by a mix of the underlying infrastructure (e.g. network and servers) and the structure of the web content itself. The thesis first inspects the available content hosting infrastructure and location, then using active measurements and *traceroute*, it looked at both QoS by measuring the RTT and the number of intermediate hops to the websites. Using Speedchecker, an Internet measurement platform, it then measured the QoE by running measurements on the page load time on both AMP and non-AMP web pages.

1.2.4 Latency in African networks

Research Question 4

What are the bottlenecks in terms of latency observed between African networks and how does this affect the overall QoS perceived by end-users in Africa?

Many African networks are characterised by high latency whether internally (in-country) or externally (towards other African countries). To gather empirical evidence of this phenomenon, a wide-scale measurement study is performed between a selected list of African countries, both within in-country networks and towards other networks.

To perform an Africa-wide latency study, the thesis relied on the Speedchecker platform, which had 850 vantage points in 52 African countries. Using active *ping* and *traceroute* measurements, both intra- and inter-country latencies were revealed, providing an exact picture of delays across the continent. The study was run over a period of three months with repeated measurements at different times of the day.

Using the data collected, the thesis further explored delay patterns by cluster countries into groups of high connectivity. The goal is to detect the strengths and weaknesses of the connectivity in the African Internet. This was achieved by using the *Louvain* clustering algorithm [24].

1.2.5 Impact of localised Internet infrastructure

Research Question 5

What are the factors impacting the development of localised Internet infrastructures and what are the effects of their growth on local content hosting and distribution in Africa?

In order to improve content delivery, localising Internet infrastructure such as IXPs and DCs is critical. This thesis first explores the factors impacting the development of localised Internet infrastructure and then using a multi-level maturity model, it rates the different African countries localised Internet infrastructure's maturity to connect local and regional networks and provide a robust local Internet ecosystem. The thesis also explored two success stories, which are the Kenyan and Nigeria IXPs. Both case studies provide some important lessons that can be used to inform policymakers in the African region, on how to improve the local Internet infrastructure in a country.

Second, using an econometric statistical model, called the fixed-effects model, it estimates the effects of the scale of an IXP on the local content activity of a country.

The model evaluates the effects of several parameters such as available average bandwidth, market concentration, Gross Domestic Product (GDP), the number of cable landing stations, etc.

1.3 Research focus and organisation of the thesis

1.3.1 Methodological choices

This thesis is a collection of individual pieces of research carried out at different points in time and forms the basis of this monograph. The main aim of the research was to provide snapshot of the current challenges of content delivery in Africa. As such, this thesis relies heavily on primary data sources (Internet measurements) and existing secondary data sources e.g. from technical reports and to a lesser extent on conference and journal articles. Fundamental research in the area is scarce as the Internet ecosystem as a whole is very dynamic and constantly changing. Therefore, this thesis focuses mainly on the data retrieval and statistical analysis components, making sure any methodology used is reproducible rather than on focussing on any specific theoretical framework. It also proposes novel methods to compare performance metrics e.g. using clustering, a technique which has not been used before in the area of networking.

1.3.2 Thesis main components

The thesis consists of eight chapters starting with the Introduction Chapter 1, which provides some background and context and elaborates on the problem statement. Chapters 2 and 3 present the existing literature and the scientific context of this research work and provide an overview of the instrumentation used to carry out the measurements and provides a summary of the different datasets and data collection campaigns used in this thesis.

Chapters 4 provides a first-hand analysis of mobile Internet usage trends in a township area, in Cape Town, South Africa. Secondly, it presents the results of a targeted analysis of Internet usage in a community wireless network, which provides both locally hosted cloud-based services (file sharing, chat, etc.) and *paid* (but subsidised) Internet connections to users living in the township area.

In chapter 5, to have a better understanding on where Africa's local content is hosted and how it is distributed, the thesis performs an in-depth study on a corpus of more than a thousand web sites, namely local news websites. Then, through another study specifically looking into public sector use cases, the performance of cloud-based services is examined. In both of these studies, the thesis reveals how the lack of hosting infrastructure and circuitous routing can have an impact on the QoS.

Chapter 6 presents and evaluates two different methods of content delivery one based on pricing (zero-rating) and the other on performance (QoS). Both techniques are meant to reduce the cost of Internet access to the end-user. The chapter provides an in-depth performance analysis of the Facebook's Free Basics programme and of the AMP service. It evaluates their potential to promote the delivery of local content in low-resource settings.

Chapter 7 deals with the connectivity situation in African countries. The thesis performs a deep-dive into inter- and intra-country latency by running active measurements from different regions in Africa. The results were compiled in the form of a latency matrix, from which several conclusions were made about the state of interconnectivity in Africa.

Building on the findings from the previous chapters, Chapter 8 proposes a series of recommendations to "democratise" access to local content. It focuses on the development of local Internet infrastructure and the discusses the factors impacting the growth of national data infrastructure in African countries. Using a multi-level maturity model, IXPs in Africa are categorised based on their scale and maturity. Finally, the thesis proposes the following hypothesis, *that increasing the scale of an IXP increases the local content activity (i.e. hosting and distribution) in a country.*

As a conclusion, a summary of the research findings and contributions of this thesis is presented in Chapter 9, as well as some elements of future work and lessons learned.

Internet Penetration in Africa (2000 - 2017)							
Countries	**2000**	**2005**	**2010**	**2014**	**2015**	**2016**	**2017**
Angola	0.1	1.1	2.8	10.2	12.4	13	14.3
Benin	0.2	1.3	3.1	6	11.3	12	14.1
Botswana	2.9	3.3	6	36.7	37.3	39.4	41.4
Burkina Faso	0.1	0.5	2.4	9.4	11.4	14	15.9
Burundi	0.1	0.5	1	1.4	4.9	5.2	5.6
Cabo Verde	1.8	6.1	30	40.3	42.7	50.3	57.2
Cameroon	0.3	1.4	4.3	16.2	20.7	23.2	23.2
Central African Republic	0.1	0.3	2	3.6	3.8	4	4.3
Chad	0	0.4	1.7	2.9	3.5	5	6.5
Comoros	0.3	2	5.1	7	7.5	7.9	8.5
Congo	0	1.5	5	7.1	7.6	8.1	8.7
Cote d'Ivoire	0.2	1	2.7	19.3	38.4	41.2	43.8
Dem. Rep. of the Congo	0	0.2	0.7	3	3.8	6.2	8.6
Djibouti	0.2	1	6.5	10.7	11.9	13.1	55.7
Egypt	0.6	12.8	21.6	33.9	37.8	41.2	45
Equatorial Guinea	0.1	1.1	6	18.9	21.3	23.8	26.2
Eritrea	0.1	0.2	0.6	1	1.1	1.2	1.3
Eswatini	0.9	3.7	11	26.2	25.6	28.6	30.3
Ethiopia	0	0.2	0.8	7.7	13.9	15.4	18.6
Gabon	1.2	4.9	13	38.1	45.8	48.1	50.3
Gambia	0.9	3.8	9.2	15.6	16.5	18.5	19.8
Ghana	0.2	1.8	7.8	25.5	31.4	34.7	37.9
Guinea	0.1	0.5	1	6.4	8.2	9.8	11.4
Guinea-Bissau	0.2	1.9	2.5	3.3	3.5	3.8	3.9
Kenya	0.3	3.1	7.2	16.5	16.6	16.6	17.8
Lesotho	0.2	2.6	3.9	22	25	27.4	29.8
Liberia	0	0	2.3	5.4	5.9	7.3	8
Libya	0.2	3.9	14	17.8	19	20.3	21.8
Madagascar	0.2	0.6	1.7	3.7	4.2	4.7	9.8
Malawi	0.1	0.4	2.3	5.8	9.3	11.5	13.8
Mali	0.1	0.5	2	7	10.3	11.1	12.7
Mauritania	0.2	0.7	4	10.7	15.2	18	20.8
Mauritius	7.3	15.2	28.3	44.8	50.1	52.2	55.6
Morocco	0.7	15.1	52	56.8	57.1	58.3	61.8
Mozambique	0.1	0.9	4.2	9.2	16.9	17.5	20.8
Namibia	1.6	4	11.6	14.8	25.7	31	36.8
Niger	0	0.2	0.8	1.2	2.5	4.3	10.2
Nigeria	0.1	3.5	11.5	21	24.5	25.7	27.7
Rwanda	0.1	0.6	8	10.6	18	20	21.8
Sao Tome and Principe	4.6	13.8	18.8	24.4	25.8	28	29.9
Senegal	0.4	4.8	8	17.7	21.7	25.7	29.6
Seychelles	7.4	25.4	41	51.3	54.3	56.5	58.8
Sierra Leone	0.1	0.2	0.6	6.1	6.3	11.8	13.2
Somalia	0	1.1	1.2	1.6	1.8	1.9	2
South Africa	5.3	7.5	24	49	51.9	54	56.2
South Sudan				4.5	5.5	6.7	8
Sudan	0	1.3	16.7	24.6	26.6	28	30.9
Togo	0.8	1.8	3	5.7	7.1	11.3	12.4
Tunisia	2.8	9.7	36.8	46.2	46.5	49.6	55.5
Uganda	0.2	1.7	12.5	16.9	17.8	21.9	23.7
United Rep. of Tanzania	0.1	1.1	2.9	7	10	13	16
Zambia	0.2	2.9	10	19	21	25.5	27.9
Zimbabwe	0.4	2.4	6.4	16.4	22.7	23.1	24.6

Table 1.1: Internet Penetration in Africa since 2000 (Source: ITU)

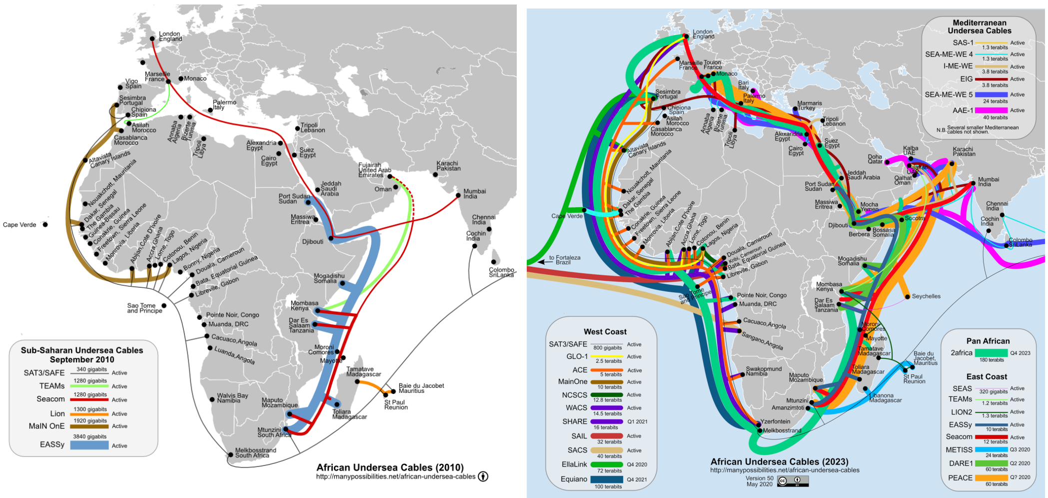
Chapter 2

Background

This chapter provides some background information about the Internet landscape in Africa as well as the techniques employed to study the challenges with content delivery. First, it presents the evolution of physical infrastructure and it explains the different obstacles along the content delivery chain. Second, it discusses the different data collection techniques used in this thesis and third, it provides a detailed description of the different Internet measurements tools used in the studies of this thesis.

2.1 Internet growth in Africa

The African Internet landscape has changed quite drastically in the last 15 years with a steep increase in Internet penetration rate (2.1% to 39.3% from 2005 to 2020 according to the International Telecommunication Union (ITU)[25]), making the continent the fastest-growing region in terms of Internet growth. Over the years, the increasing demand for Internet connectivity has triggered large investments in infrastructure such as fibre optic cables (sub-sea and terrestrial) and data centres all around the continent. In Sub-Saharan Africa, the mobile penetration rate increased from 28% to 44% in the last ten years, with about 456 million unique subscribers as per the 2020 GSM Association (GSMA) report on the Mobile Economy. It is expected that by 2025, there will be 625 million mobile phone subscribers representing a penetration rate of 50% [26]. And with a population median age of 19.7 (2020 UN estimates), mainly connected on mobile phones, the demand for reliable and fast access to content is on the rise.



(a) 2010 (b) 2020

Figure 2.1: Submarine cables evolution between 2010 and 2020

Back in 2005-2010, a lot of African countries, especially in Sub-Saharan Africa, were still relying on satellite communications as the only source of international connectivity. Satellite links are known to be slow, unreliable and often expensive [27]. As the demand for better connectivity spurred - largely attributed to the rapid growth in mobile phone usage - the continent witnessed a large-scale undersea cable construction effort. Institutions such as the World Bank and the African Development Bank increased the support provided to projects in the telecommunications sectors, especially, with regards to up-hauling fibre connectivity across the continent. Until 2009, the west coast of Africa was mainly served by only one cable (called SAT-3). Only after 2009, the first new-generation cables arrived in Africa, namely SEACOM, on the east coast. Figure 2.1 shows how the sub-sea ecosystem evolved between 2010 and 2020, expecting to cross the 650 Terabit per second (Tbps) threshold (overall forecasted capacity) by 2023, with two major cable systems planned for 2021 Equiano (100 Tbps by Google) and 2Africa (180 Tbps by Facebook)[1].

The continent witnessed equally important growth in the terrestrial cable ecosystem. According to Hamilton Research[28], Africa's international Internet bandwidth reached 15.289 Tbps in 2019 as compared to 0.295 Tbps in 2009. Africa's terrestrial fibre optic cable networks increased by 3-fold, connecting more than 50% of the population of sub-Saharan Africa. Many private companies such as Liquid Telecom and MainOne have been a catalyst in their respective regions, deploying cross-border fibre

[1] Africa Undersea Cables Version 50, last accessed on 2021-04-20, https://manypossibilities.net/african-undersea-cables/

networks. As it can be seen from Table 2.1, many African countries have invested quite extensively in the past ten years, building up terrestrial fibre connectivity which had a major impact on Africa's backbone and metro markets. A lot, therefore, has been achieved in the last decade towards improving access to the Internet on the continent. (Terrestrial Fibre networks include both operational and dark fibre lines).

Terrestrial Fibre infrastructure growth 2009 - 2020

Metric/ Year	Terrestrial Fibre networks (in km)	Operational Fibre Optical Networks (in km)	% of population in sub-Saharan Africa within 25-km range of an operational fibre network (in million)	International bandwidth (in Tbps)
2009	465,659	278,056	259 (30.8%)	0.445
2013	905,259	524,847	371 (41.8%)	2.023
2014	958,901	564,091	403 (43.5%)	2.982
2015	1,019,649	622,930	436 (45.8%)	4.506
2016	1,179,010	762,167	469 (48.1%)	5.930
2017	1,254,413	820,397	522 (52.1%)	7.939
2018	1,270,500	936,102	556 (54.2%)	10.250
2019	1,389,475	1,025,441	584 (55.2%)	15.289
2020	1,400,000	1,072,649	620 (55.9%)	18.0 (est)

Table 2.1: (Source: Africa Bandwidth Maps) Terrestrial fibre optic cable and bandwidth growth in Africa 2009-2020.

Another important technical component of the Internet is the data hosting infrastructure. In the last few years, there has been sustained development of colocation facilities in Africa, which is a vital component of a robust African Internet. In 2010, the number of Tier 3 colocation facilities recorded by the Data Centre Map[2] was 22 in 3 African countries (with 16 being in South Africa). In 2020, the number jumped to 63 in 13 countries but in a rather skewed distribution (South Africa: 33%, Nigeria: 15.9%, Mauritius: 14.3%, Kenya: 9.5% and Morocco: 7.9%). However, despite the dramatic demand for hosting facilities is on the rise, fuelled by increase in connectivity levels and traffic volume in the region, most of Africa is still lacking adequate data centre facilities. In a report from the Internet Society in 2017, the lack of local content infrastructure and Content Delivery Networks (CDNs) was identified as a major hurdle to the wider and deeper usage of Internet in Africa. "Hosting content locally significantly reduced the latency and cost of content delivery, in turn making it more accessible for the local community." [29]

[2]Data Center Map website, last accessed on 2020-04-28, https://www.datacentermap.com

The (un)availability of hosting infrastructure has a direct incident on the Quality of Experience (QoE) and the cost in accessing content. As seen throughout this thesis, most of African content is hosted outside of Africa and coupled with a poor peering fabric, Internet traffic is most of the time routed across the world through the US and Europe before being delivered back to users in Africa. That said, it is important to note that in the last few years, there have been more and more CDNs coming to Africa. Akamai[3], a key player in content delivery, has been on African shores since 2013. They now have presence in more than 30 locations in Africa[30]. Cloudflare[4] a leading CDN, is in 14 different cities across Africa. In 2019, Microsoft opened it's first data centres in Africa (in South Africa) to provide it's cloud services to business in the region[31].

Finally, in the recent years, there is an interesting phenomenon, whereby Content Providers (CPs) such as Google, Facebook and Microsoft, are not only investing in data centres and Points of Presence (PoPs) in Africa to increase their edge caching capabilities, but they have started to deploy their own cable infrastructure[5], to facilitate data flow between their Data Centres (DCs) around the world.

2.1.1 Barriers to universal Internet access

Significant focus is currently being laid on the role of universal access to foster economic development in emerging regions, underpinned by broadband connectivity. However, the number of connected Africans (39.3%) remains considerably low as compared to Europeans (91%), as per the ITU[32]. In the GSMA 2019 report, it is mentioned that 30% (300 million) Africans live in areas of "Coverage gap", where there is no signal coverage from any mobile broadband network (at least 3G). And 46% (460 million) are in the "Usage gap", where they live within reach of mobile broadband network but are not using the Internet, mainly because of issues of affordability both to Internet services and devices (see Figure 2.2). The lack of mobile broadband infrastructure is partly due to high Capital Expenditure (CAPEX) costs – especially in remote and rural areas. As an indication, the average additional annual cost of mobile coverage sites is 18% in rural (over urban areas), and 35% more in remote sites due to heavy initial costs of backhaul, power and civil works[33]. Whilst access to adequate networking infrastructure, especially in rural and remote areas

[3]Akamai CDN, last accessed on 2020-04-28, https://www.akamai.com

[4]Cloudflare CDN, last accessed on 2020-04-28, https://www.cloudflare.com

[5]Equiano Cable, last accessed on 2020-04-28, https://cloud.google.com/blog/products/infrastructure/introducing-equiano-a-subsea-cable-from-portugal-to-south-africa

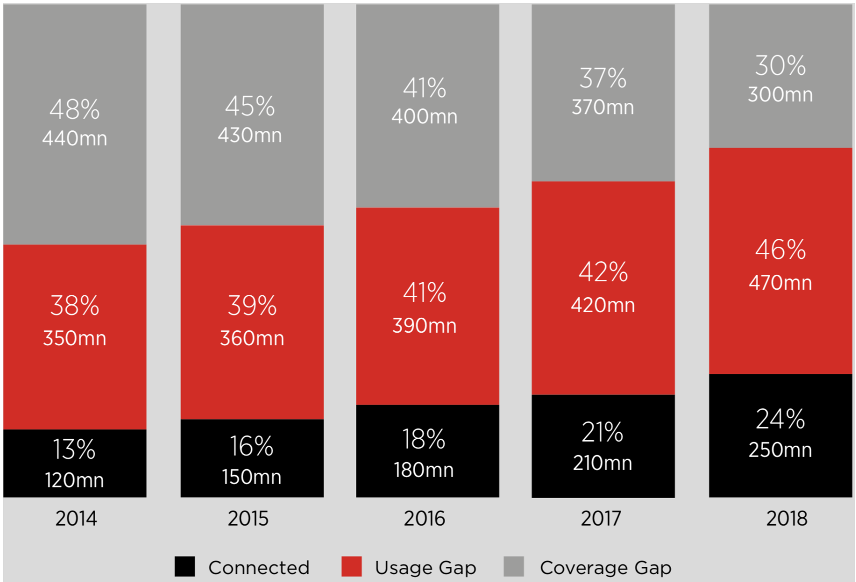


Figure 2.2: Source: GSMA2019. Percentage of Sub-Saharan African population connected to mobile internet over time. While the 'coverage gap' (people living within the service range of a mobile broadband network) decreased over time, the 'usage gap' (people living within the range of a mobile broadband network but are not using mobile internet) increased.

of Africa, remains a major obstacle, another yet bigger obstacle is affordability of Internet access namely through mobile broadband[34].

In order to meet the objective of bringing around 1.1 billion Africans online through good quality, reliable and affordable Internet access by 2030, Africa will need to invest around USD 100 billion in infrastructure – as reported by the ITU Broadband Commission[35]. The report mentions about 250,000 additional base stations and an additional of 250,000 km of fibre are required to reach universal access.

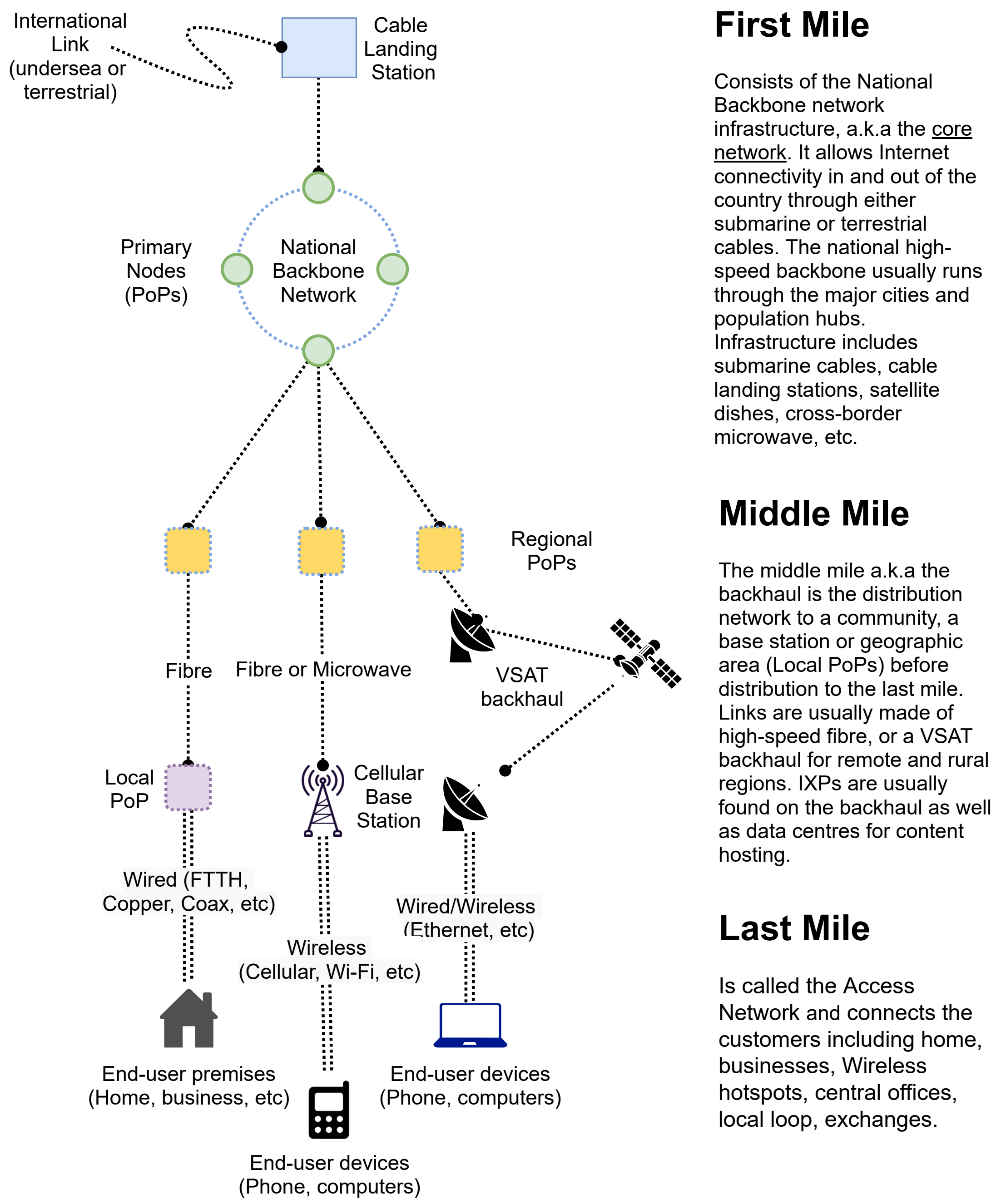


Figure 2.3: Source: Author, adapted from various, including BroadbandCommission and others. Components of a broadband network from first to last mile.

As such, to meet the above objective it is very important to assess the connectivity gaps of the existing infrastructure. Digital infrastructure can be broadly be divided into three main categories: (1) infrastructure that enables connectivity including mobile and fixed networks, metro and backhaul, national backbone, and submarine cables for international connectivity, (2) infrastructure that holds the content such as data centres, content delivery networks or clouds and (3) the infrastructure that enables end-user to consume the data such as mobile phones, laptops, sensors, smart vehicles, etc. To understand the challenges of the broadband network value chain to deliver affordable, reliable and good quality Internet access, it is important to understand the bottlenecks in the underlying three components which constitute a broadband network: the first mile, middle mile and last mile (see Figure 2.3).

First mile and international connectivity The first mile provides international and cross-border connectivity. The main components in the first mile are submarine cables, landing stations and satellite dishes. All of the seaboard countries in Africa (38) today are connected to submarine cables, except for Eritrea. The other 16 landlocked countries rely mostly on terrestrial fibre or satellite links and usually have agreements with neighbouring countries to carry their traffic in and out of the country (see Figure 2.4. South Africa is the country with the highest number of subsea cables landing, followed by Egypt and Djibouti (mostly because of transit cables in their region). While the continent has witnessed a rapid expansion of submarine fibre capacity in the last ten years (x10 increase), a few challenges remain. For example, there is a need to develop policies that will help liberalise the market for first mile, preventing market consolidation by a specific company, which provides both transit and operate a mobile network. Figure 2.4 shows a map of Africa, the submarine and terrestrial fibre network and the cable landing ports.

By overlaying population data from LandScan[6], fibre optic infrastructure data from Telegeography[7] and Network Startup Resource Center (NSRC)[8], regions where interventions are required can easily be identified – see Figure 2.4. It can be observed that there is a high concentration of fibre in urban regions (where most of the population are concentrated) as opposed to less populated areas. Furthermore, whilst most of the African nations are connected via submarine cables, 16 countries are landlocked and rely exclusively on terrestrial fibre to allow them to connect internationally (some countries still rely on satellite for their backup links). The "backbone" terrestrial fibre network is very essential to bring connectivity to both the landlocked countries and to regions which are offshore, sometimes thousands of kilometres inland. As Internet connectivity is mostly driven by mobile connections, ensuring that the base stations receive adequate bandwidth is important for a reliable Internet. The map in Figure

[6] LandScan, last accessed on 2020-04-28, https://landscan.ornl.gov/landscan-datasets

[7] Telegeography Submarine Cable map, last accessed on 2020-04-28, https://www.submarinecablemap.com/

[8] African Terrestrial Cable map, last accessed on 2020-04-29, https://afterfibre.nsrc.org/

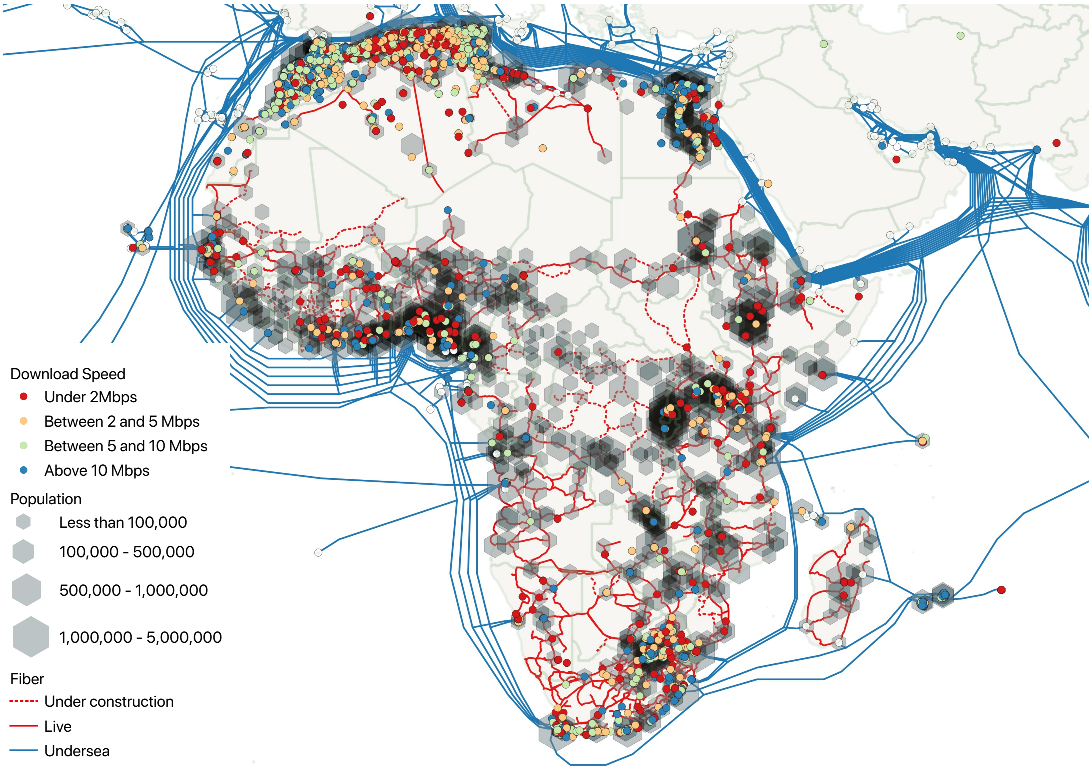


Figure 2.4: Visualisation of fibre infrastructure in Africa, population density and download speed, illustrating connectivity gap between urban and rural regions. Source: afterfibre.nsrc.org, Telegeography, SpeedChecker and NaturalEarth population dataset

2.4 is made of both submarine and terrestrial cables that are live and under construction, on which population density data and speedtest data from Probe Application Programming Interface (API)[9] have been overlaid. This map clearly shows an urban and rural divide where most of the fibre network is concentrated in the most populated areas. It is estimated that around 25% of inhabitants in Africa are located within a 10-Km range of a fibre PoP, which is a higher percentage as compared to other regions of the world (see Table 2.2). To some extent, it confirms the hypothesis that rural and remote areas are often less-provisioned and networks not provisioned by the fibre network are more likely to suffer from lower signal speed and capacity. This contributes to widening the so-called connectivity and usage gaps in rural areas.

Middle mile and national connectivity The middle mile refers to the network or components that constitute the national backbone infrastructure. Normally, the national backbone will connect multiple cities in a loop, such that if one main hub goes

[9]SpeedChecker Platform, last accessed on 2020-05-20, https://www.speedchecker.com

down, traffic can still be re-routed through the other cities. The national backbone is therefore used to connect the critical infrastructures such as DCs, Internet Exchange Points (IXPs), national agencies, etc. Figure 2.4 shows the countries which have a well-developed national backbone, while some others still lagging behind. Africa being a continent of vast territories, deploying a high-speed fibre optic network backbone nationwide is very costly. It can also be observed that the fibre network is concentrated in the metro areas, leaving the remote and rural areas out of the equation. According to AfricaBandwidthMaps[10], in Q3 2019, Africa's operational fibre optic cable network reached 1,474,983-km (including the live, under construction and planned cables).

An increasingly important national infrastructure is an IXP. IXPs provide national Internet Service Providers (ISPs) and other networks a platform (layer-2 switch) to peer and exchange traffic. It allows local traffic to stay local and hence contribute to reducing latency between networks in the same country. For example, they help connect data centres in a country[11], especially those operated by diverse ISPs. Currently, there are 46 active IXPs located in 42 cities in 34 countries in Africa[12]. As Chapter 8 demonstrates, not all African countries are on the same level playing field with regards to the maturity of their national data infrastructure. Many African countries do not have a fully operational IXP and they are all operating at different levels of maturity. As seen later in this thesis, there are many factors influencing the development of the local Internet infrastructure in the "middle mile" tier.

Last mile connectivity and end-user connectivity

The Last mile network, also called "Access network", is the final hurdle of the network which connects the end-users to the rest of the telecommunication infrastructure. Last mile connectivity is usually operated on fixed destinations (Fibre to the Home (FTTH), Asymmetric Digital Subscriber Line (ADSL), etc.) or mobile (2/3/4G). Local area networks such as a campus network or a community wireless mesh are examples of last-mile networks. Good quality connectivity therefore depends heavily on the network provisioning of the last-mile, which is usually a bottleneck, with regards to the Quality of Service (QoS). Whilst tremendous improvements occurred in the last decade on the African continent, a large portion of the population in Sub-Saharan Africa (35%) is living in the so-called "coverage gap" [36]. This is

[10] AfricaBandwidthMaps, last accessed on 2020-06-12, http://www.africabandwidthmaps.com/

[11] An interesting success story is NAPAfrica, which is an IXP operated in conjunction with Teraco, a carrier-neutral data centre). The IXP is completely free of charge for the clients of the data centre, and has over time, become one of the major IXPs in South Africa

[12] AF-IX active IXPs, last accessed on 2021-02-20, https://www.af-ix.net/ixps-list

because in many cases, there is little Return on Investment (ROI) associated to rural and remote places, telecom operators tend to favour the more populated urban regions, where there is a higher demand in mobile data usage.

Table 2.2: Source ITU. Number and percentage of inhabitants within the 10, 25, 50 and 100-Km range in different world regions

Region	**Africa**	**Arab States**	**Asia & Pacific**	**The Americas**
Route Kilometres	542,365	202,772	10,255,072	700,586
10-km Range	256,462,370 (24.6 %)	61,051,850 (16.67%)	488,596,419 (12.23%)	168,670,975 (17.45 %)
25-km Range	521,164,133 (50 %)	144,149,542 (39.36%)	1,338,550,614 (33.51 %)	344,155,482 (35.61 %)
50-Km Range	755,490,608 (72.4 %)	203,843,049 (55.65 %)	2,349,596,751 (58.81 %)	437,840,864 (45.3 %)
100-Km Range	904,875,669 (86.7)	n.a.	n.a.	n.a.
Total Population	1,043,329,213	366,271,679	3,995,005,442	966,494,926

2.1.2 Scarcity of local content and content hosting facilities

The web has long been considered an open and participatory platform [37, 38, 39, 40]. Early advocates of the Internet's democratising power believed that the web would give more people a voice to better participate in their own communities and countries. Nevertheless, while access has improved, wealthier and better-connected countries create and host the majority of Internet content. For instance, research conducted by Graham *et al.* [41], has shown how Wikipedia's user-generated content not only largely represents Global North views but is also overwhelmingly produced by users in the Global North. This is also reflected by where most of the content hosting facilities are concentrated (see Figure 2.5.

From a more social perspective, lack of content in local African languages further reduces the ability to access and use the Internet. "Although social networking platforms, educational services, and entertainment are relevant in many countries worldwide, content must be in familiar languages to be relevant, which is often an issue in Sub-Saharan countries whose populations are not always comfortable in the official government language. While one might assume this mainly impacts international content, it is also true for local content, including e-government services, as

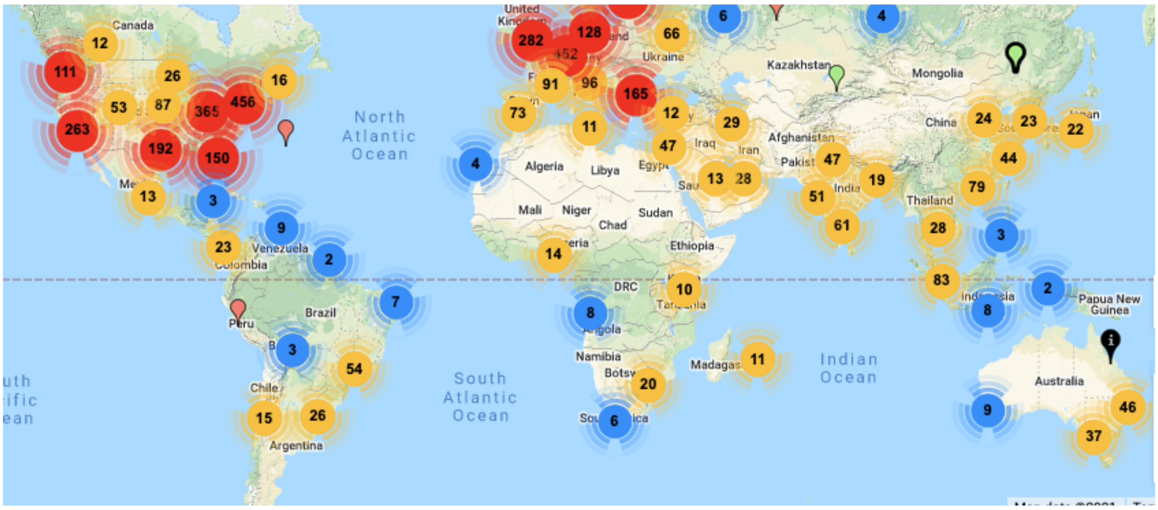


Figure 2.5: Concentration of data centres around the world. Africa hosts 1.70% of data centres globally. Source: Datacentermap.com

most of the time they are not offered in local languages [29]". Access to "relevant content" is one of the major indicators of the Web Index[13].

A study by Ballatore *et al.* revealed that only eight African countries have a majority of content that is locally produced. This was achieved by focusing on search results generated, in the 188 countries where Google was available, when searching for capital cities [40]. Most of the content comes from the United States (US), and to a lesser extent, from France. Ballatore *et al.* refer to this phenomenon as "digital hegemony", whereby producers in a few countries define what is consumed by others.

Financial and skill barriers are only some of the factors affecting who is able to participate in the digital representations of the world and who does not [42]. Other factors, in the African context, are related to the Internet topology which is characterised by limited national and international interconnections and peering. Low levels of Internet penetration and disposable incomes [43], have been a disincentive for businesses that optimise the distribution of web content through deployment of CDNs to invest in Africa [12, 21].

2.2 Data collection techniques

To be able to have a full understanding of the underlying dynamics of the Internet, data on the state of the network should be collected, processed and analysed. This

[13] Web Foundation Web Index, last accessed on 2021-02-10, https://thewebindex.org/

is achieved using Internet measurement techniques which can be categorised into two main families, active and passive Internet measurements.

2.2.1 Active measurement

Active measurements consist of injecting network traffic into a live network at one end and observe the resulting behaviour of the injected packets at the other end. It is expected that the results observed would give a good indication of the performance of Internet protocols in a real-world scenario. However, active probing should be carried sparingly as they can potentially alter the behaviour of the network and skew the end results, especially on resource-constrained networks. There are different metrics that can be measured using active measurements, depending on the network protocol being studied, examples are latency, packet loss, jitter, Domain Name System (DNS) resolution time, throughput, etc. Active measurements can also reveal the path a packet takes to reach its final destination. To achieve the above, active measurements rely on a set probing tools. A more exhaustive list of tools is provided by CAIDA[14].

Round-Trip Time (RTT) is measured using the *ping* (Packet Internet Groper), usually bundled with most operating systems. It uses the Internet Control Message Protocol (ICMP). First of all, ping allows reachability testing i.e. it checks whether the destination IP is available. Then, it sends *ICMP ECHO request* packet to the destination IP and measures the time it takes to receive an *ICMP ECHO reply* from the destination IP. The result is measured in milliseconds (ms).

To reach its final destination, a packet traverses multiple hops along its path. *traceroute* is a tool that helps reveal this information, usually quite useful when troubleshooting an Internet link. Traceroute works by sending IP packets with incremental TTL values. The hop (router) which receives the IP packet with a TTL of zero, will send an ICMP Time Exceeded packet to the sender to report the "error". The hop which rejects the IP packet, includes its network interface IP address in the error message. Therefore, if an IP packet has a TTL of n and is sent through the network, the router located at n hops on the path, would return its IP address, and will continue doing so as long as the path to the destination is greater than n hops [44]. The result consists of a series of hops which responded to ICMP probes.

The number of hops and the path itself can be different every time a traceroute is run. These can vary depending on the conditions of the underlying networks such as congestion or changing network restrictions. Load-balancing is a common cause of

[14] CAIDA Tools, last accessed 2021-05-21, `https://www.caida.org/tools/taxonomy/measurement/`

asymmetric path, which means that two IP packets from the same source can take different paths to reach the same destination. The Paris-traceroute helps to mitigate this problem by changing the sequence number in the ICMP header (or the checksum in the UDP packet) [45].

Just like Paris-traceroute, many other tools were built atop *traceroute*, for various purposes. One of them is *traIXroute*, which can help to detect the presence of IXPs along the path [46]. The tool makes use of different available datasets namely PeeringDB [47] and Packet Clearing House [48]. Both of these datasets provide information about IXPs at a global level.

With regards to bandwidth measurements, the *pathchar* tool [49] provides throughput information for each hop and it uses a technique similar to traceroute by sending probes with incremental TTL values. Pathchar injects traffic by varying the size of the packet for each hop it tries to reach along a path, this is how the available bandwidth between each hop is determined. Another very common tool is *Iperf* [50], which is a tool that needs to be installed at both ends (the sender being the client machine and the receiver is the server machine).

The above-mentioned tools allow to perform measurements on one or two user-controlled end-points. However, if one wants to run wide-scale measurements from a variety of vantage points, it is best to make use of distributed measurement platforms. Each platform has a specific goal e.g. M-Lab NDT[51], which is a crowd-sourced speedtest tool, focuses on throughput measurements while RIPE Atlas [52] performs ping, traceroute, DNS, HTTP and TLS measurements. More details about the RIPE Atlas platform is provided in section 2.3. Bajpai *et al.* [53] provides a comparison of different measurement platforms and their associated use cases based on: (1) the scale, coverage and life-span of the measurement network, (2) the types of probe deployed (hardware, software or hybrid), (3) the metrics being measured, (4) the data collection and storage architecture, (5) the popularity and usefulness of the measurement platform as a tool for empirical research.

In this thesis, active measurements techniques are used to: (1) retrieve QoS metrics towards local content (Chapter 5), (2) understand the intra- and inter-country latency (Chapter 7) and finally (3) in Chapter 6 to uncover the benefits and challenges of using Facebook's Free Basics and Google Accelerated Mobile Pages (AMP) from an end-user's perspective.

2.2.2 Passive measurement

The aim of running passive measurements is to analyse the flow of packets at a specific collection point on the network. Passive measurements involve capturing, storing and analysing IP packets at different level of granularity depending on the information of interest. The collection points can vary, it is normally either on the sender's network or on the receiving end's network but it can be anywhere in between as well. One advantage of passive techniques is that there is no need to introduce additional probing packets into the network, as they can potentially bias the measurement. It is therefore less intrusive. On the downside, passive measurements are localised and provide a view from the collection point only. Aspects such as QoS or QoE can only be inferred from passive measurements. The metrics that can be collected from passive techniques can be broadly classified in two main categories which are network monitoring and performance.

When packet-level information is captured, usually in the form of packet traces, each layer of the network stack can be explored. For example, when analysing a DNS request using *tcpdump*[15] or *Wireshark*[16] (both packet analyzers), the application-level DNS query can be seen, the underlying UDP packet as well as corresponding Ethernet dataframe. Passive measurements tend to generate lot of data and therefore storage of packet traces can be a challenge. For this reason, sampling techniques such as sFlow [54] are used. Traces are normally captured and stored in *pcap* files using the *libpcap* library, which can be used to both read and write pcap files. Furthermore, passive data can be used to emulate a traffic flow in a network. By re-running the captured packets, a researcher can mimic the flow of traffic in real-time and analyse the behaviour and other parameters of the network.

There is currently no wide-scale and distributed passive measurements platforms existing. However, there are many Internet datasets that are made publicly available for research purposes such as Scans.io[17] or Censys.io[18]. One important aspect to consider when dealing with passive datasets is access to private information. As such, extra care should be taken when handling sensitive data such as browsing behaviour of users, IP addresses to protect the privacy of the subjects. Tramwell *et al.* [55] explored the associated risks to end-user privacy when handling large amount of Internet measurement related data.

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[15] TCPDUMP, last accessed on 2021-02-02, `https://www.tcpdump.org/`

[16] Wireshark, last accessed on 2021-02-02, `https://www.wireshark.org/`

[17] Stanford Internet Research Data Repository, last accessed on 2021-02-02, `https://scans.io/`

[18] Censys, last accessed 2021-02-10, `https://censys.io/`

This thesis makes use of passive measurement techniques to study the Internet usage behaviour of users in a township area. Details about the measurement campaign and results presented in Chapter 4.

2.3 Internet measurement platforms

Internet measurement platforms are infrastructures that are dedicated to periodically running Internet performance and topology measurements. The platforms are broadly categorised as either passive (network traffic monitoring) or active (network probing). Over the years, several such platforms and tools [51, 56, 57, 58, 59, 60, 61, 62, 63] have been deployed at strategic locations in access, backbone, behind residential Internet gateways, as well as on user devices. These platforms provide network telemetry, for example to monitor the quality of fixed-line or mobile access networks. The platforms implement a range of measurement techniques to infer network performance, including through client-side probing and passive monitoring, as well as through remote probing architectures. Remote probing of fixed-line access networks, for instance, is done by injecting packets and using responses received from residential gateways to infer broadband link characteristics [64].

A number of these platforms provide software-based solutions and include Netalyzr [59], SpeedChecker[19], Ookla SpeedTest[20], Glasnost [62], and ShaperProbe [63], all of which provide a software interface for end users to measure broadband performance. The Netalyzr tool, e.g., communicates with a collection of servers to measure key network performance and diagnostic parameters from the perspective of the broadband user.

The hardware-based platforms, on the other hand, use dedicated devices – often termed probes – to run both user-defined measurements or pre-defined measurements with minimal end-user participation. Internet users tend to voluntarily host these probes for the benefit of being able to monitor, among other things, whether their network providers indeed adhere to the advertised service offerings. Internet Service Providers (ISPs), on the other hand, tend to use the data from such platforms to identify and address problems in its eyeball network, as well as to evaluate the QoS experienced from their customers' perspective. Popular among these hardware-based platforms are RIPE Atlas [52] and perfSONAR [56]. RIPE Atlas, for example, is a distributed measurement infrastructure deployed by the RIPE NCC and consists

[19]SpeedChecker Measurement platform, last accessed on 2021-04-30, `https://www.speedchecker.com/speed-test-tools/`

[20]Ookla Speedtest, last accessed on 2021-04-30, `https://www.speedtest.net`

of small hardware probes and larger server-like anchors. The hardware probes (see Figure 2.6) run active measurements to determine network connectivity and global reachability, whereas the anchors serve as dedicated servers that can act as sources and sinks for the network measurement traffic. Similarly, perfSONAR is a network monitoring framework focused on measuring end-to-end performance for paths crossing multi-domain networks.

(a) Version 3

(b) Version 4

Figure 2.6: RIPE Atlas Hardware Probe

Other systems have been developed mostly for local wireless and mobile networks. Some of the popular mobile platforms include Netradar [58], Portolan [61], MySpeedtest [64], and more recent platforms include Nornet [65], Monroe [60] and LiveLab [66]. Netradar, for instance, is a client-server based mobile Internet measurement infrastructure that makes use of measurement targets that are deployed in the cloud and globally distributed to allow users to run performance tests.

While many of these measurement platforms and tools produce the expected results and have gained substantial deployments in many parts of the globe, their availability in Africa and other parts of the developing world still lags. For example, M-Lab has only seven live servers in Africa. Given the limited number of measurement vantage points and limited network resources in Africa, data regarding the Africa's Internet operations remains limited. Generating this high fidelity data could be achieved with the deployment of these measurement probes and conducting short and long term measurement campaigns.

Table 2.3 provides a summary of measurement campaigns, the type of measurement performed and the platform used.

Table 2.3: List of measurement campaign and platform used throughout this thesis

Chapter	Study	Measurement type	Platform	Details
4. Internet usage in a township community	Mobile internet usage	Passive	MySpeedTest	Used Myspeedtest app to collect usage from mobile phones
	Internet traffic analysis in a community network	Passive	Traffic capture	Collected the Internet traffic at firewall (pfSense) in pcap files.
5. Accessing local content	Content Hosting	Active	RIPE Atlas	Performed traceroute and RTT measurements towards local news websites
	Cloud computing	Active	RIPE Atlas	Performed traceroute and RTT measurements towards cloud services
6. Alternative content delivery mechanisms	QoE analysis on Freebasics	Active	Custom code	Freebasics study: QoE measurements from two vantage points using custom-built scripts.
	QoE analysis on Google AMP	Active	Speedchecker Probe API	AMP study: QoE measurements using Speedchecker API
7. Latency study	Intra and Inter-country latency analysis	Active	Speedchecker Probe API	Performed ping and traceroute measurements from probes towards SpeedTest servers.

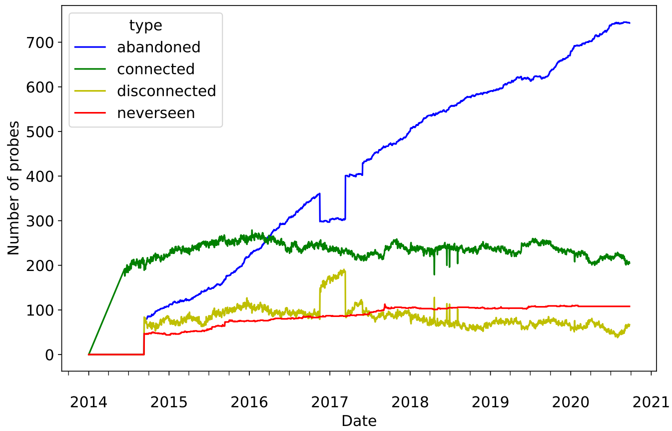
2.3.1 RIPE Atlas platform

The RIPE Atlas[21] platform consists of measurement vantage points called "probes" and measurements servers known as "anchors". RIPE Atlas is a hardware based measurement platform[22], which means that the hardware used are mostly homogeneous (with different versions). Both probes and anchors can be used to run a series of active measurements. Example of available tests are: ping(6), traceroute(6), DNS(6), HTTP GET, TLS, etc. Anchors have additional functions such as operating as a measurement target/collector. As at January 2021 (see Figure 2.7, RIPE Atlas has deployed 10511 probes and 457 anchors across the world. However, in general most of the measurement infrastructure is concentrated in the developed regions, i.e. in the US and Europe. In Africa, as at January 2021, there were 231 active RIPE Atlas probes distributed in 126 Autonomous Systems (Autonomous Systems (ASs)) (39 of which have both IPv4 and IPv6 connectivity). This represents a coverage of 7.3% only.

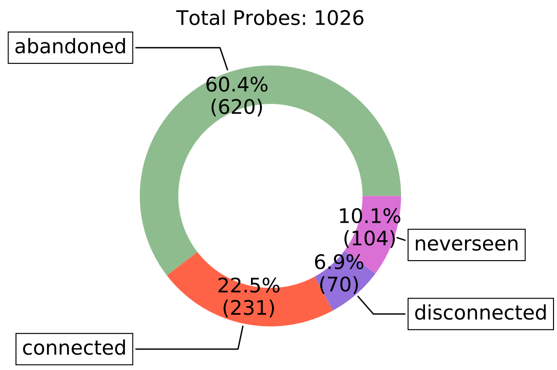
This section provides some information on the distribution of RIPE Atlas probes on the African continent and evaluate how good or how bad coverage is in terms of

[21] RIPE Atlas platform, last accessed on 2021-04-21, `https://atlas.ripe.net`

[22] In 2019, RIPE Atlas released VM anchors that can be installed as a standalone virtual machine, without the need to have a dedicated server. In 2020, they also released software probes, that can be installed on a Linux system such as a Raspberry Pi. These new functionalities were not captured in this thesis as they are recent.



(a) Deployment of RIPE Atlas 2014-2021



(b) RIPE Atlas Probes status (January 2021)

Figure 2.7: Status of RIPE Atlas Probes in Africa

number of network that can actively be probed by RIPE Atlas. To run this study, data is collected from multiple sources. First, using the RIPE Atlas API[23], data is retrieved on the probes residing in Africa. The API provides full details on the probe including the IP address, Autonomous System Number (ASN), geolocation, etc. Using the AFRINIC[24] Allocation dataset[67] the percentage of active probes vs allocated ASNs is then computed. This provides a rough idea of coverage. The PeeringDB dataset [47] is used to categorise the different types of networks. Figure 2.8 shows the distribution by network type showing that all network types are covered. Enterprise networks are the worst performing in terms of maintaining probe connected.

[23]RIPE Atlas platform API, last accessed on 2021-04-21, https://atlas.ripe.net/docs/rest/

[24]The African Network Information Centre (AFRINIC) is the Regional Internet Registry (RIR) for the African region.

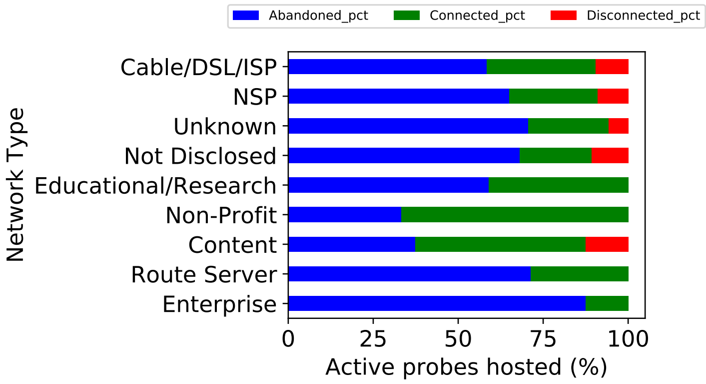


Figure 2.8: Probe distribution by network type showing that all network types are covered. Enterprise networks are the worst performing in terms of maintaining probes connected (January 2021).

2.3.1.1 Geographical distribution

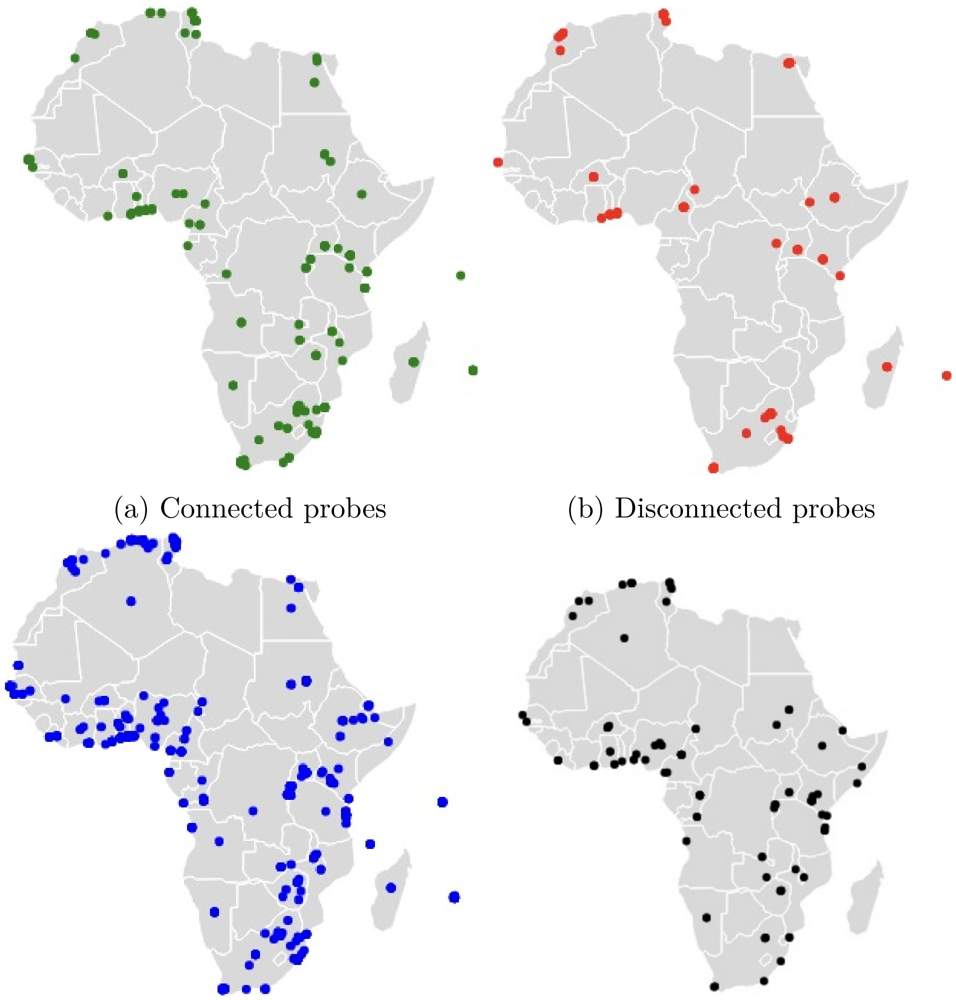
There are currently 231 active probes scattered in 32 countries (see Table 2.4). The number of abandoned probes are quite high both with regards to the number of countries impacted and the number of networks concerned. Figure 2.9 shows the geographical distribution of probe across Africa. The number of active probes has been more or less stable over the years (approx. 200) and the number of disconnected probes around a 100. However, the number of abandoned probe, has steadily increased.

Probes	Countries	ASN	% of ASN allocated
Connected	32	126	7.3
Disconnected	16	45	2.6
Abandoned	40	212	12.3

Table 2.4: Summary table of probes distribution

2.3.1.2 Topological distribution

As seen in Fig 2.10, not all networks are equally covered in their respective countries of allocation. Egypt which has a very large market has one of the lowest number of probes available. On the contrary, some smaller economies such as Burundi, has a high score. This is because, there are not many networks in this country and therefore coverage is high.



(a) Connected probes (b) Disconnected probes

(c) Abandoned (d) Never Connected

Figure 2.9: Geographical distribution of probes by status

The country with the most number of probes is South Africa with a 120 actives probes over a total of 240 (50% offline). Most other countries have very low level of availability as shown by Figure 2.11.

2.3.2 Speedchecker

Speedchecker ProbeAPI is a commercial platform that is globally distributed and which is most widely used for bandwidth test. At the time of writing, it had coverage in 172 countries. It also provides multiple network tests such as Ping (TCP/ICMP), DNS, Traceroute, HTTP GET and web/video performance tests. The probes are both software and hardware based and Speedchecker maintains three types of probes: (1) Android probes – which are installed on mobile phones (2) PC probes – installed

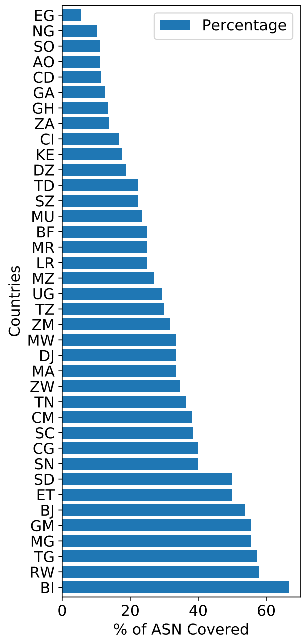


Figure 2.10: ASN Coverage by country

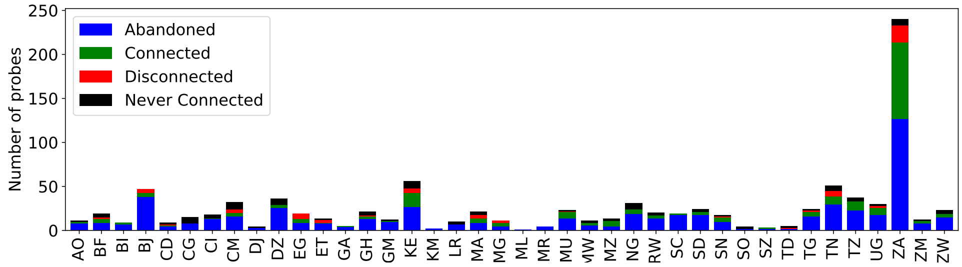


Figure 2.11: Probe status by number. As compared to other countries South Africa has the highest number of probes. They also have the highest number of ASs allocated. In most cases, the 'abandonment' phenomenon is existing

on Windows computers of subscribers and (3) Router probes – installed on DD-WRT router usually found on customer premises.

2.3.2.1 Coverage

The ProbeAPI platform was utilised mainly in Chapters 6 and 7 in which multiple measurement campaigns using *ping* and *traceroute* tests were performed using 850 software probes present in 319 different networks in 52 countries. Figure 2.12 shows the currently visible probes in Africa.

At the time of the study, there were 219 probes in South Africa and 193 probes in Algeria, 87 in Egypt, 62 in Morocco and the rest scattered in various other African

Figure 2.12: Number of Speedchecker probes online (last accessed 20 April 2020) in Africa with which intra- and inter-country measurements were carried out. (Source: www.maplatency.com)

countries. Altogether, the Speedchecker Probe API covered at least 20% of all networks in any specific country in Africa, where the probes are present.

2.3.2.2 Comparing RIPE Atlas and Probe API

Table 2.5 provides a list of the main differences between RIPE Atlas and ProbeAPI. One important note is that the Speedchecker PC and Android probes are quite widespread (100,000+) as opposed to a few thousand globally for RIPE Atlas. However, RIPE Atlas has a better up-time scores the fact that they are run on dedicated hardware. Probe API software probes become unresponsive when the host i.e. the PC/Android phone is disconnected, hence making probes' availability very volatile.

In a study done by Speedchecker.com [68] in 2015, Varas *et al.* claimed that at any given moment there are around 84,000 probes online and during a normal working day, the number can reach as high as 290,000. This shows the high volatility of the probes though they argue that the high number of probes counterweighs the issue of volatility, making the platform a reliable one for one-off measurement campaigns. For measurement campaigns that require constant probe availability, RIPE Atlas is a better option.

Table 2.5: Differences between RIPE Atlas and Speedchecker

Probe Type	**Coverage**	**Avail-ability**	**Connec-tivity**	**Hardware/ Software type**	**Test coverage**	**Exten-sibility**
Speedchecker Router probes	3000-4000	99%	LAN	CPE Devices/ DD-WRT	PING, HTTP, Traceroute	NO
Speedchecker PC probes	100,000+	10%	WI-FI LAN	PC/ Windows	PING, DNS, Traceroute, HTTP, Pageload,Video	YES
Speedchecker Android probes	100,000+	50%	WI-FI 3G 4G	Android OS	PING, DNS, Traceroute, HTTP, Pageload,Video	YES
RIPE Atlas Hardware probes	10,000+	99%	LAN	TP-Link NanoPI	PING, DNS, Traceroute, SSL, NTP	NO
RIPE Atlas Hardware Anchors	663	99%	LAN	Homogeneous	PING, DNS, Traceroute, SSL, NTP	NO

2.3.3 Mobile measurement using MySpeedTest app

There are many ways to study the network usage of mobile phones. One way is to capture passive log data at the network operator's level and try to infer statistics on usage. Since it is usually almost impossible to have access to the carrier's data, unless there are some prior agreements, passive log measurements is not an option. The other way to proceed is to collect passive and/or active measurements directly from the mobile device. A few such platforms are available, some of them being proprietary and others open-source. The measurement platform typically consists of a software probe installed on the mobile device and a central database, where measurement data is captured.

The four main measurement Android-based platforms available are: Netalyzr [69], Mobiperf [70], Mobilyzer [71] and MySpeedTest [72]. They are all more or less equivalent, especially that all of them are different implementations of the core library of

Mobilyzer. In the design of the experiment in Chapter 4, only users with Android smartphones were intentionally selected, as they were quite representative of the population where there is a clear dominance of Android phones as opposed to other type of operating systems [73]. MySpeedTest was the preferred choice as it is open-source, widely deployed in South Africa and it proved to be rather efficient based on the experience gathered from the previous studies [74], [75], [76]. Figure 2.13 shows the control interface and data usage view of the MySpeedTest application.

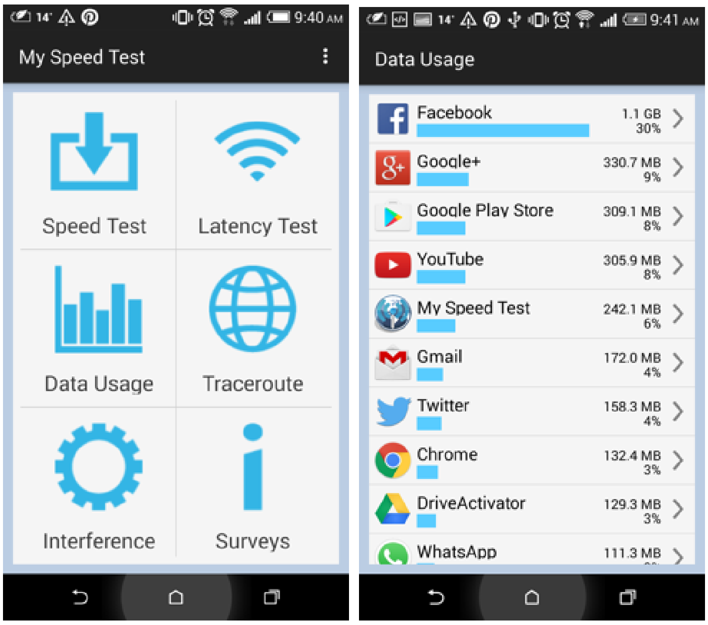


Figure 2.13: MySpeedTest app interface

The MySpeedTest is an Android application developed by the GTNoise Lab at Georgia Tech [72]. Apart from collecting application usage, the tool also collects data on throughput packet loss, latency and jitter to known online services from the user's smartphone. There is also a feature to collect traceroute data to a specified location as instructed by the user. The application also collects some metadata such as network operator's name, SSID, data cap plan and so on. Table 2.6 provides a list of relevant tables from which performance and usage data are extracted. In the study on mobile usage (Chapter 4), only usage data is analysed and not the performance data. To collect data on Internet usage, passive measurements are carried out in the background while the user is browsing. It monitors the data consumption of all Android apps installed on the system. The mobile app is installed on users mobile phone after explicit consent is received and all required details provided to the end-user, namely about their privacy.

Table 2.6: List of relevant tables from MySpeedTest database

Table	*Description*
application	Contains details of the application name and package
application_use	Contains details on the application's network usage (bytes sent and received), whether the application is running in foreground or background
network	Gives information about the network used in a specific measurement. Information such as the network type (Cellular or Wi-Fi), base station ID, GPS coordinates, etc. can be retrieved, if those information are made available.
measurement	Is a metadata table, that contains information about a measurement, the time it was carried out and whether it was manually triggered or scheduled.
device	Contains data on the measurement device. Information such as the network country code, the phone brand and model, software version, data plan type etc. are stored. Confidential data such as phone number are hashed.

Chapter 3

Literature Review

This chapter discusses the existing literature on Internet usage, web performance measurements, Internet topology discovery, traffic characterisation and content delivery. Particular emphasis is laid on prior research studies done in developing regions, as they share the same context as the work in this thesis. Section 3.7 highlights the differences in approach and techniques used in this research.

3.1 Internet usage and traffic characterisation

Most online activities are now on mobile, especially in Africa, it is therefore important to understand how end-users are experimenting with online activities such as browsing, online video streaming, social media usage and so on. As such, this thesis presents previous works from both the quantitative and qualitative angles and provides some insights into techniques used to gather usage data.

There has been prior research on mobile application usage in slum communities in different parts of the world. For example, Rangaswamy *et al.* carried out an anthropological study of everyday mobile Internet adoption among teenagers in a low-income urban setting in India [77]. They discovered entertainment to be a major aspect of technology infusion, contributing to enhancing the ICT related skills and abilities of users. Wyche *et al.* also conducted studies in Viwandani, a slum in Nairobi, articulating some of the ways in which Facebook is used for “hustling”, or ad hoc income generation [78]. Both of these studies provide rich perspectives into how slum youth use mobile Internet.

In 2015, Sambasivan *et al.* performed an interesting experimental study of how SmartBrowse, a tool to allow users to monitor their Internet usage, helped users to reduce their mobile data expenses but at the same time, increase web pages views [79].

There is a small set of literature found on mobile Internet usage in township communities in South Africa. In 2009, Kreutzer made a study of 66 secondary school grade-11 students in a low-income area in Cape Town [80]. The study revealed that more than 97% of respondents actually owned a mobile phone or used one on a regular basis. The study also suggests that mobile Internet was quite popular with 83% of the respondents accessing the web on a typical day.

In 2011, Donner, Gitau and Marsden studied mobile Internet-only usage in an urban setting in South Africa [81]. They used an ethnographic action research approach to study the challenges and practices of mobile data usage in a resource-constrained setting. Research subjects were observed after being given training and they found out that most of them were still using the Internet on their mobile phones, especially for entertainment and communication - months after receiving the training.

Furthermore, several studies have performed quantitative examinations of mobile Internet usage in Africa. In 2013, Chetty *et al.* used passive and active measurement methods to collect performance and usage data from both home routers and mobile phones [75]. One of the objectives was to compare broadband performance on different connection types and see whether users were getting the performance advertised by their Internet Service Providers (ISPs). A combination of measurement tools is used: BISmark [82] on home routers, MyBroadband [83] and MySpeedTest [72]. They found that (1) users were not getting the advertised speed from their respective ISPs (2) mobile broadband users have a higher throughput than fixed-line users; and (3) high latency to popular websites and services affected performance and quality of service.

In 2015, Mathur *et al.* used a multi-factor approach triangulating data from three distinct sources: semi-structured interviews, surveys and the MySpeedTest application to study characteristics of mobile broadband usage of high-income versus low-income participants across South Africa. Although the study does not specifically target resource-constrained regions, it uncovers similar patterns especially in terms of application usage. For this study, they interviewed more than 300 participants, made 43 interviews and collected measurement data from 121 mobile devices.

Finally, there is very little literature on previous studies done with regards to traffic characterisation in developing regions. Johnson *et al.* [84] gathered and analysed network traces from a rural wireless network in Macha, Zambia in 2010. They deployed a traffic monitoring system which collected usage data for two consecutive weeks. They found that Internet usage patterns in rural Africa was different from the developed and well-provisioned regions. They observed a dominance of web traffic (68.45%) as opposed to P2P traffic which was prominent in urban settings. Instead users preferred to share large files via USB keys. The most popular online applications were web browsing and email, a fact which was later verified through interviews of Internet users in the community. It was also observed that the Internet was used as the main source of news, whereby news websites were heavily accessed during peak times. This particular point about the "cost of accessing news website for local content" motivated the studies in chapters 5 and 6.2, whereby they look into where local content from news websites is hosted and the QoE users experience to access the content.

3.2 Web performance measurements

The number of Data Centres (DCs) across African countries is increasing [85], and there is a growing number of Internet Exchange Points (IXPs) to exchange local traffic[1], along with international content providers and Content Delivery Networks (CDNs) installing nodes in Africa of recent. Notwithstanding, these improvements in Africa's Internet provision, most content in the continent, even local websites, are hosted and are delivered from overseas [86]. As an illustrative example, almost all the Alexa's top 50 websites[2] by African countries are foreign websites. In terms of DCs, Google reports having nine of them in the United States, four in Europe, two in Asia, and none in Africa. Conversely, in order to bring content closer to the users, Google has deployed a number of cache infrastructure by deploying Google-supplied servers inside local network infrastructures and Internet service providers[3]. Several studies have analysed the users' overall experience and satisfaction in a more global context. For example [87, 88] demonstrated that there is a correlation between web latency and user retention.

To this end, a few studies have strived to characterise the performance of Africa's Internet infrastructure, including performance of the web ecosystem. Fanou *et al.* [89] studied the content delivery infrastructure for Africa and found that, as of 2016, much of the continent's web content was being served from the US and Europe. Their analysis of websites showed that large web infrastructure deployments were not common in Africa, such that even regional websites would host their services abroad. The authors also showed that many of Africa's web performance problems were due to significant inter-AS delays in the continent, which also contributed to local ISPs not

[1] List of African IXPs, last accessed on 2021-02-19, http://www.af-ix.net/ixpsmap

[2] Alexa Top Websites, last accessed on 2021-02-19, https://www.alexa.com/topsites

[3] Google Data center location map, last accessed on 2021-02-19, https://www.google.com/about/datacenters/locations/

sharing their cache capacity. Similarly, Gupta *et al.* [12] studied ISP interconnectivity between various African regions and discovered most of the intra-Africa traffic was exchanged circuitously, whereby local Internet paths often detoured through Europe.

Zaki *et al.* [15] focused their study on Ghana and based their findings on measurements collected between 2012 and 2014. They analysed web performance data of top Alexa's websites in Ghana from different locations. They found out that bandwidth was not really an issue but instead Domain Name System (DNS) resolution was a big bottleneck. The actual time to download a web page was just a fraction of the end-to-end page download, the biggest chunk being attributed to DNS resolution. The other parameters which were found to be affecting the overall page load time is the Transport Layer Security (TLS)/Secure Sockets Layer (SSL) handshake. By caching DNS responses they were able to decrease page load time by five times.

In this thesis, the concept of web performance is evaluated from different angles. First, the thesis studies how users in resource-constrained settings are affected by low performance when using their mobile phones. Secondly, it investigates the effectiveness of using a zero-rated service with regards to web QoE as opposed to using alternative paid services. And finally, in chapter 6.2 it further explores web QoE by evaluating a web acceleration platform, namely the Google Accelerated Mobile Project (AMP), in the African context.

3.3 Internet topology and end-to-end performance measurements

A handful of studies have recognised the traffic engineering problems in Africa's Internet topology [21, 13, 90, 22]. Primarily, these studies have highlighted Internet performance issues that are attributed to a lack of peering amongst Africa's ISPs. Due to this, models that aim to predict global latencies have consistently modelled Africa as the slowest in the world [91]. Other studies have also looked at inefficient DNS configurations, a lack of local content caching servers, as well as a lack of cross-border cable systems [89, 15, 29].

A recurring observation from these studies has been the general lack of local and regional peering among African ISPs, which has resulted in a high percentage of Africa's Internet traffic being exchanged via intercontinental routes, notably through Europe. These studies have also consistently shown that end-to-end Internet latency is comparably much higher in Africa than in most other continents.

Gilmore *et al.* [22] performed a logical mapping of Africa's Internet topology, highlighting the router level and AS[4] level paths followed by intra-Africa traffic. Their analysis was based on traceroute data obtained from measurements conducted from a single vantage point in South Africa towards all AFRINIC allocated IP addresses. The key limitation of this work was that it only contained one-way paths from South Africa shedding limited light on the structural and performance characteristics of most other countries. The resulting logical topology, which contained one-way paths from South Africa to the rest of Africa, showed that most of the routes traversed the United Kingdom, Scandinavia and the USA.

Gupta *et al.* [90] showed that around 66% of Africa-based Google cache content consumed by end users in South Africa, Kenya and Tunisia was being served through intercontinental links. The analysis from this study[5] also showed that Africa's ISPs do peer to each often much more through European IXPs such as London and Amsterdam, than they do at national or regional IXPs.

Ali *et al.* [92] did a similar Internet performance analysis of South Asian countries by running end-to-end performance measurements using the PingER[6] platform. This study, although it was not carried out in Africa, provides good insights into the situation in another developing region. They argue that Internet performance is highly correlated with economic development metrics, where it was found that an increase in economic growth of 1.3% corresponds to an increase in Internet speed by 10%. The metrics used in the performance analysis are: latency (RTT), packet loss, reachability, throughput and the Mean Opinion Score (MOS). They found similar trends such as indirect routing through Europe, Singapore or Hong Kong. As a result, overall end-to-end latency between neighbouring countries was found to be high, which explains the moderate MOS score of the region.

Finally, Chavula *et al.* [13] used five nodes from the CAIDA Archipelago platform to conduct logical topology mapping for Africa's national research and education networks. They found that over 75% of Africa's inter-university traffic followed intercontinental routes. Although more extensive than [22], these restricted studies only provide insights into a small number of countries and networks. Effectively, the first study to take a wide-area perspective was by Fanou *et al.* [21]. This work launched traceroute measurements from 90 ASes. Their results too showed a lack of direct

[4]An Autonomous System (AS) is a collection of IP routing prefixes under the control of one or more network operators. It refers to network operators.

[5]Gupta *et al.* increased the number of vantage points, although they still launched probes from a small set of countries.

[6]PingER Project, last accessed 2021-02-20, https://www-iepm.slac.stanford.edu/pinger/

interconnection amongst African ISPs. It was also shown that many ASes that are geographically collocated in the same countries had much longer AS to AS paths than would have been expected. The average end-to-end RTTs for continental paths were between 50ms and 150ms, whereas for intercontinental routes, the average RTTs were around 200ms. Most of the latencies between 100ms and 400ms (95%) were through Europe, whereas the latencies above 750 ms were for paths that went through satellite links.

3.4 Access barriers to local content and cloud-based services

Prior studies have suggested that limited availability, accessibility and affordability of the underlying Internet technology is a key hindrance to the adoption of cloud computing developing countries [9, 10]. Apart from the limited access to the Internet infrastructure, concerns related to security and privacy of cloud-based information processing have been cited as a critical factor slowing adoption of the cloud. For South Africa, survey results by Brenda Scholtz *et al.* [9] suggested that 'system performance' and 'privacy of data' were the biggest technical concerns that could hamper implementation of cloud computing in public organisations. Similarly, Gillwald *et al.* [10] identified limited and costly broadband as major barriers to adoption of cloud computing services in South Africa, Tunisia, Nigeria, Ghana, and Kenya.

Early advocates of the Internet's democratising power believed that the web would give more people a voice to better participate in their own communities and countries. The web has long been considered an open and participatory platform [37, 39, 38, 40, 93]. Nevertheless, while access has improved, wealthier and better connected countries create and host the majority of internet content. For instance, research conducted by Graham *et al.* [41], has shown how Wikipedia's user-generated content not only largely represents Global North views but is also overwhelmingly produced by users in the Global North.

From a more social perspective, lack of content in local African languages further reduces the ability to access and use the Internet. Although social networking platforms, educational services, and entertainment are relevant in many countries worldwide, content must be in familiar languages to be relevant, which is often an issue in Sub-Saharan countries whose populations are not always comfortable in the official government language. While one might assume this mainly impacts international content, it is also true for local content, including e-government services, as most of the time they are not offered in local languages.

A study by Ballatore *et al.* , by focusing on search results generated in the 188 countries where Google was available, when searching for capital cities revealed that only eight African countries have a majority of content that is locally produced [40]. Most of the content comes from the United States (US), and to a lesser extent, from France. Ballatore *et al.* refer to this phenomenon as "digital hegemony", whereby producers in a few countries define what is consumed by others.

Financial and skill barriers are only some of the factors affecting who is able to participate in the digital representations of the world and who does not [42]. Other factors, in the African context, are related to the Internet topology which is characterised by limited national and international interconnections and peering. Low levels of Internet penetration and disposable incomes [43], have been a disincentive for businesses that optimise the distribution of web content through the deployment of CDNs to invest in Africa [12, 21].

3.5 Content delivery in developing regions

Several studies have looked into the performance aspects of content delivery in developing regions. First, there is a series of work that explores the policy angle of content delivery in developing countries. Kende *et al.* [20] looked at the infrastructure needed to deliver content in Sub-Saharan Africa. They discussed the importance to have carrier-neutral DCs to attract CDNs and other local hosting solutions, not only to create a competitive market but to increase the amount of content hosted locally.

In May 2017, Internet Society (ISOC) published another report on the benefits of local content hosting [94]. They looked at the Rwandan case, where the Ministry of Youth and ICT decided to repatriate a selection of Rwandan websites back in the country. They found that there was a drastic drop in page loading times which was a direct benefit for the end-users. It was also interesting for content providers and website developers as it expanded business opportunities. In 2017, the OECD published a report named "Spanning the Internet divide to drive development", outlined why the content providers should adapt their service delivery based on the speed and the quality of the Internet access in the targeted areas.

With regards to alternative means of content delivery, there is a body of knowledge around content caching and delivery in slow and intermittent networks [95, 96, 97, 98]. Raza *et al.* proposed xCache, a bandwidth aware caching system, which they deployed and tested on three university campuses [97]. They found out xCache, together with some other web optimisation solutions, could reduce page load time by more than 50% [97]. More recently, Ahmad *et al.* [98] introduced GAIUS a content ecosystem that enables content to be delivered locally. Whilst GAIUS is currently being deployed, they were able to demonstrate how the system enabled and promoted the creation of local content. The above mentioned technologies are mostly experimental and have not been largely deployed.

In this thesis, two globally deployed initiatives, were evaluated. The first one being Free Basics, which is considered to be a novel "cost-based" (namely zero-rated) content delivery mechanism. Free Basics has been deployed in several developing countries around the world, namely developing countries. There has been a vigorous debate around the provisioning of “free” services from Over-The-Top (OTT) providers, as it raises questions on anti-competitive practices as well as concerns on net neutrality [99]. Furthermore, the behaviour of mobile Internet users is greatly influenced by mobile pricing practices [76]. In a comparative study of mobile usage between US and South African users, Chen *et al.* found that South African users tend to use more Wi-Fi connections, whenever available, except for zero-rated services provided by their network carrier.

On the other hand, the Google Accelerated Mobile Pages (AMP) is a "performance-based" content delivery model. In a study commissioned by Google in 2017, Forrester Consulting conducted a Total Economic Impact (TEI) study to evaluate the potential Return on Investment (ROI) publishers are making with the deployment of AMP [100]. They based their study on a composite organisation representative of existing AMP eCommerce vendors and found out that there was an increase by 20% in profit growth from sales conversion rate. They also found a 10% year-over-year increase in AMP site traffic, which also resulted in profit growth.

3.6 Peering ecosystem in developing countries

Peering and interconnection is a highly researched topic. Many studies have highlighted the benefits of *keeping local traffic local* through a robust peering ecosystem [101, 102, 103, 104]. In a paper from 2013, Chatzis *et al.* [104] surveyed publicly available data to gather information about IXP . They highlighted the critical differences among various IXPs around the world. They discussed how IXP-driven innovation has shifted the Internet marketplace in Europe and how this has been a game-changer for content delivery. Böttger *et al.* [105] looked into how the impact of IXP growth on Internet routes. They observed a diversion of routes, away from central Tier-1 ASes. Interestingly, they also observed that larger IXP (usually commercial ones) have moved away from public IXP peerings, whereas smaller IXPs have been participating more.

With regards to prior literature covering the developing countries a study from Muttitanon *et al.* [106], showed how Internet cost can be reduced by means of an IXP . They took as case study the Thailand Internet ecosystem, where they mathematically analysed two models (with and without an IXP) and predicted the cost benefit. They found that running an IXP can reduced by 2.5 times the cost of the country. Venkatta *et al.* [107] performed a region-centric analysis of Internet peering and investigated how the distribution of network business type, peering policy, and traffic level varies across the five regions. They observed low traffic networks in Africa, medium traffic to high traffic in Latin America, Europe and the US. Interestingly, the Latin American region has the largest share of medium traffic networks. In terms of peering policy distribution, they found that open peering was the dominant peering policy in all five regions. However, in North America and Asia Pacific higher portions of networks adopt non-open (i.e., selective and restrictive) peering policy due to their larger share of high traffic networks.

Furthermore, the peering ecosystem in the Latin-American region has been in the limelight in the recent years, thanks to sustained development in their peering ecosystem. From a research carried out in 2013, Galperin *et al.* [101] talked about the maturity of IXPs in the LATAM region using a 3-tier evaluation (Stage 1, Stage 2 and Stage 3) system. They mentioned about several enabling factors such as a competitive telecommunications market. Quite recently, Carisimo *et al.* [108] investigated the role of governments in the creation and maintenance of IXPs , the characteristics of the IXPs (members, growth over time, etc.). They combined different publicly available datasets and socio-economic information to run their analysis.

With regards to studies focusing on Africa, the Internet Society produced a first report on the barriers to Africa's Internet development in 2013 [109]. They performed two case studies of Kenya (KIXP) and Nigeria (IXPN) and found that IXPs contribute to reducing the use and dependency of international bandwidth. ISOC produced an updated report in June 2020 and explained how traffic pattern shifted, with almost 70% of traffic being local [110]. Along the same vein, Fanou *et al.* [111] explored the bottlenecks in the Africa peering ecosystem with 37 IXPs (in 2017) and provided some theoretical optimisation to the peering fabric in the region.

3.7 Summary

As seen earlier, there are multiple studies that have analysed the level of connectivity, quality and resilience of the African Internet ecosystem. Many of the studies, which focused on mapping the Internet topology and the early studies (circa 2007), were based on measurements carried out from a single vantage point only (e.g. Gilmore *et al.* [22]). As more vantage points and measurement platforms were deployed, many other studies started looking into the interconnectivity issues in Africa [21, 12, 13]. Many of these studies advocated for better peering policies to reduce the level of circuitous routing and the latency between local networks. As opposed to these previous studies, this thesis performs a multi-angle analysis of the problem of content delivery in low-resource networks.

Understanding "locality of interest" is a key concept in this thesis. Previous studies provide some limited information on Internet usage patterns as most of them were carried out several years ago [84, 112] and many parameters such as type of devices, bandwidth, Internet services have changed. This thesis provides an updated perspective of Internet and content needs and consumption patterns from an under-provisioned area in South Africa, which to some extent is reflective of the situation in other bandwidth-constrained areas of Africa.

This thesis builds on the rationale is that the future success of local services depends on low delay underlying connectivity within the whole region (not leaving the region). Many of the previous studies in sections 3.2 and 3.3 provide some hints about the issues with high delay and circuitous routing. However, none of them deeply explored the causality behind high delays, and the implications of the topology configurations observed. Using a novel technique based on clustering and expanding the scope of the research covering 52 countries and 319 networks, this thesis achieves the above goals on a scale not seen before.

Finally, most of the papers and reports focused on the benefits that IXPs bring to the local ecosystem, but none of them empirically evaluated the impact of IXPs on local content activity. By means of a proxy (number of Country-code Top-Level Domains (ccTLDs) and number of web pages), in chapter 8, this thesis tries to establish a relationship between the scale of an IXP (IXP growth) and local content activity within a country.

Chapter 4

Understanding Internet usage in a low-resource environment

This chapter firstly presents a study of the Internet usage patterns of an under-resourced community living in a township area near Cape Town, South Africa. Using a mixed-method approach, the study performs an analysis of mobile Internet use in this community, where access to the Internet was initially, and mostly, limited to mobile broadband. Next, it elaborates on the deployment efforts to help build a community network named “iNethi” in that same location, which provides free access to local services and low-cost access to the Internet. Furthermore, following the deployment of the community network details, about a 6-month network measurement is provided. The key topics covered included passive mobile and network measurements, traffic characterisation, Internet usage patterns, wireless mesh network architecture and social considerations around the deployment of a community wireless network.

4.1 Analysing mobile Internet use in a township area in South Africa

Despite the tremendous growth in Internet-capable mobile device adoption [113], Internet usage and access to data is limited in South Africa by prohibitive costs and unequal coverage [114]. Yet, the high cost of communication has not deterred the growth of mobile data usage in the less-privileged areas such as in the South African townships[1]. In fact, mobile data usage growth in township areas has outpaced the average usage growth across the whole of South Africa [115]. The drop in the price

[1] “Townships” refers to urban informal settlements in South Africa, where people were historically displaced during Apartheid period based on their ethnicity. They are the poorest urban communities in South Africa.

of smartphones and faster mobile broadband connectivity (3G/LTE) in those areas completely disrupted the rate at which mobile data is being consumed. Figure 4.1 shows how data usage drastically evolved for Vodacom with consumption increasing by almost 500% between 2011 and 2015 [116].

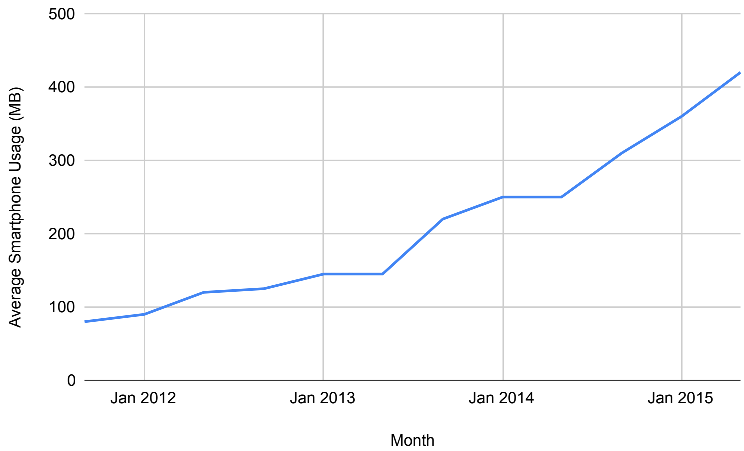


Figure 4.1: Smartphone data usage (source: Vodacom)

Yet, mobile data is expensive relative to the incomes of township residents. The World Bank estimates that half of South African's urban population lives in townships and informal settlements, accounting for 38% of working age citizens, and home of nearly 60% of unemployed [117]. In Khayelitsha, one of the poorest areas of Cape Town, the median average monthly income of a family of five is approximately USD 110 [118]. The study suggests an average monthly expenditure of up to USD 6-12 per user. At such a high cost, many users may find mobile data unaffordable; therefore understanding the nature of the usage patterns in lower-income townships is important, both to understand the economic consequences of mobile Internet penetration, as well as to suggest opportunities for network and application architectures to better optimise data use in these settings.

This thesis analysed the data usage patterns of mobile Internet users living in township communities in South Africa. To this end, seven high school students and seven knowledge workers from two different township communities (Ocean View and Masiphumelele) in Cape Town were recruited to participate in the research study. A mixed-method approach was used comprising two parts: (1) quantitative measurements of the usage of different mobile applications using the MySpeedTest application [72]; and (2) a survey examining users' behaviour concerning mobile Internet usage. With these two methods, the aim was to cross-validate behaviours of mobile usage collected from the measurement application with the responses received from the survey.

In 2015, Mathur *et al.* found that, in contrast to more developed regions, when data is expensive or limited, users have the tendency to be extremely cost-conscious and would employ various strategies to optimise mobile data usage [74]. This situation obviously does not encourage the extensive use of Internet technologies, which could enable resource-constrained communities to share information, communicate, generate content and make use of online educational material for their own benefit. It leaves open the complementary but important question of how users in more resource-constrained communities such as townships use mobile applications and consume mobile data. A previous study on broadband measurements in South Africa also revealed interesting data on performance bottlenecks [75]. Yet in contrast, very little is known about Internet connectivity in township communities. By characterising mobile Internet usage, this thesis attempts to build a solid understanding of the need of cellular networks users from township communities in South Africa.

Additionally, the extent to which mobile data traffic is exchanged with users who reside in the same geographic region was studied using a survey - which revealed that most of the interactions on social networks are targeted to "friends" who live roughly the in the same locality. This means that users are actually using their expensive and limited data packages to send and receive data to peers living relatively nearby.

The quantitative measurements help to investigate how much traffic is being generated for social media, communications, software updates, video streaming, and other applications, as well as how usage is influenced by economic factors such as promotional data packages and zero-rated services. Table 4.1 gives a list of services that are currently zero-rated by mobile operators in South Africa. By gathering and analysing empirical data on how mobile Internet is consumed in township areas, the results can ultimately guide researchers on the needs of mobile phone users, especially in the resource-constrained regions. The outcome of this research can provide important input for the design and deployment of alternative network architectures [119] that could reduce the cost of interconnectivity.

The study reveals the following findings, several of which contrast with previous studies in South Africa in higher-income communities:

- In contrast to communities with higher incomes, median daily data usage across users is more on cellular data networks than on than Wi-Fi. Qualitative survey results suggest that the relative inaccessibility of public Wi-Fi may induce this behaviour.

Operator	*Service*	*Description*
MTN	Wikipedia	Users can access Wikipedia and MoMaths service for free using Opera Mini.
Cell-C	Whatsapp	Whatsapp is unlimited (except voice calling) for R5 per month.
	Freebasics	Freebasics allows free access to Facebook (no videos and images available) and other free services such as news, classified and Wikipedia. None of the services have images or videos
Vodacom	E-School	Provides zero-rated access to a few educational websites.
Telkom	ShowMax VoD	Free video-on demand service available for premium users only.

Table 4.1: List of zero-rated services by mobile operators

- In contrast to communities in South Africa with more resources and higher incomes, township users consume significant mobile data on cellular networks to update mobile applications.
- As in other communities, streaming video usage is lower on cellular data networks than on Wi-Fi.

4.1.1 Research Context

South Africa has very high mobile data rates. The Research ICT Africa's (RIA) Africa Mobile Price (RAMP) report [120] shows that "the cheapest 1GB price in South Africa ranks 30 out of 51 African countries for the third quarter of 2019. In Egypt, the cheapest 1GB of prepaid data costs USD 1.41; the same amount of data in South Africa is sold for USD 7.50. Using the same measure, South Africa came last out of six large telecommunications markets in Africa last quarter (Q1 2017). The cost of 1GB of data is three times the cost of the same data amount in Ghana and Tanzania, and more than twice the cost of 1GB in Nigeria".

Other than remote rural areas, urban and periurban informal settlements in South Africa (townships) usually have decent 3G/4G coverage, however their use is limited due to lack of affordability for the average user. Internet is typically accessed using mobile phones.

The study was performed in Masiphumelele (nicknamed Masi) and Ocean View, two township areas in Cape Town, South Africa, situated between Kommetjie, Capri Village and Noordhoek. In 2010, the population in Masi was estimated at 38000[2] occupying roughly one square kilometer. The number might have increased considerably since with the arrival of immigrant workers in Cape Town townships [121]. A number of NGOs such as Living Hope[3], MasiCorp[4] and Desmond TuTu Foundation[5] have been working for the past decade to uplift the community through health care, education, youth programs and business development initiatives and there are many opportunities to develop ICT solutions to complement these services.

Just five kilometres away, there is Ocean View, another township established in 1968 with approximately 14000 inhabitants (see Figure 4.2), where school children were interviewed. Both townships are historically bandwidth-constrained communities which reveal a disparity within the realm of ICT access. At the time of this study (2016-2019), there was no public Wi-Fi available.

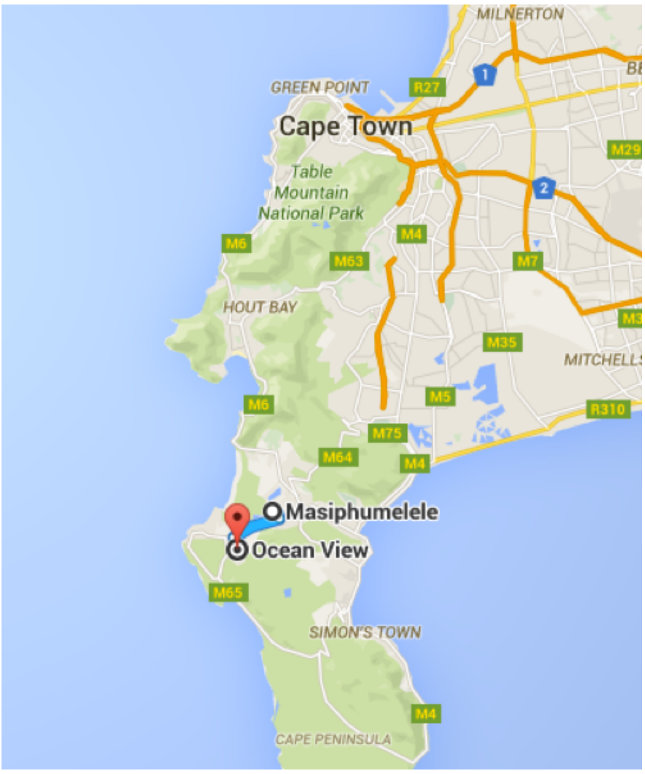


Figure 4.2: Masiphumelele and Ocean View townships

[2]Unofficial source: MasiCorp Demographics
[3]Living Hope NGO, last accessed on 2017-12-19, http://www.livinghope.co.za/
[4]MasiCorp, last accessed on 2017-12-19, http://www.masicorp.org
[5]Desmond TuTu Foundation, last accessed on 2017-12-19, https://desmondtutuhivfoundation.org.za/

Current Internet access in Masiphumelele is limited to 3G from the different providers, an Internet Café and limited Internet access at the Library (for example, no YouTube is allowed). In Ocean View, the only publicly accessible Internet service (no Wi-Fi) is at the Library where it is limited to 45 minutes per day per user and users need to get vouchers prior to getting access to the Library computer facilities. As a result most community members access the Internet through cellular connectivity. Ocean View and Masiphumelele are both fairly well covered by GSM and UTMS networks, with some very limited LTE coverage, as this is currently being deployed.

It was found that most of the users recruited have pre-paid or "pay-as-you-go" mobile plans as opposed to contract plans. They usually buy airtime or data bundles from either the nearby shops or shopping malls. To be able to use contract plans, a user must be able to prove a stable monthly source of income and a bank statement, which automatically disqualifies students and any informal worker. It is therefore very common to see that almost all mobile users in township areas are using prepaid plans. Mobile Internet is available either through time limited data bundles or directly from the airtime available, at a premium cost. Table 4.2 provides some of the entry-level data plans available, price and validity.

Users living in township areas typically buy data bundles as and when needed, usually multiple times in a week. And this mainly because of affordability issues. It must be noted that in that population group, more than 50% of the household derives a monthly income of less than R1600 (USD 110) as per a 2011 census from the City of Cape Town [118].

Access to the Internet is therefore a challenge. Not only must users rely on relatively costly mobile Internet connectivity, sometimes with very short life-span, but they also they must cope with issues of poor network performance as reported by some interviewees in the study.

4.1.2 Data Collection

The study was conducted on seven high school students from Ocean View and seven knowledge workers from Masiphumelele. The measurement experiment for lasted six consecutive weeks, where participants were told to use their mobile phones, just as they would do on any other day. As incentive and at the end of the experiment, for every participating phone, the total amount of data used by the MySpeedTest application (on 3G) was collected and each participant's phone was topped up with twice the amount that was spent conducting the study.

Table 4.2: Data plans from mobile operators

Operator	*Plan 1*	*Plan 2*	*Plan 3*	*Plan 4*
MTN	5MB R4 1-day	20MB R12 1-day	50MB R25 3-days	300MB R85 5-days
Voda-com	20MB R5 1-day	100MB R10 1-day	250MB R20 1-day	250MB R60 1-month
Cell-C	20MB R3 1-day	100MB R13 1-day	100MB R25 1-month	300MB R60 1-month
Telkom	25MB R8 1-month	50MB R15 1-month	100MB R29 1-month	250MB R39 1-month

The students were conveniently sampled as they volunteered to participate in this exercise after all grade-10 students were informed about this experiment. Grade-10 students were preferred over lower grades as they were deemed to be at an appropriate maturity level for collaboration with the researchers. Similarly, the knowledge workers were also conveniently sampled as they all work for the NGO Park in Masiphumelele. The 14 users who installed the MySpeedTest applications were surveyed.

Although the sample is rather small[6] to provide good inferential statistics, this sample gives an indication on potential usage patterns of two important subgroups of a township community, which are the two biggest users of Internet related services, whether it is for communication and social media related activities.

Furthermore, conveniently sampling the participants can introduce a bias in the data as argued by Burrell *et al.* [122]. Only participants with Android phones were selected as they were the most available. Those with either Blackberries or Windows phone, albeit very few, would not have contributed to larger sample diversity. Nevertheless to mitigate the bias introduced, those with non-android phones were interviewed separately and their feedback were recorded on the survey form.

To determine usage, the amount of data spent on different classes of applications on a daily basis, was analysed. By aggregating the data, the study then characterised usage as follows:

[6]The author acknowledge the small size of the population and therefore the findings cannot be generalised. However, the results of this first study was taken into consideration when building the *iNethi* network, which allowed students to connect freely to local and Internet services.

- Number of applications
- Mean daily usage across all users
- Most used applications on Wi-Fi
- Most used applications on Cellular
- Usage of zero-rated applications

The quantitative analysis was followed by a user survey, which was conducted in the last week of the study. The aim of the survey is two-fold: (1) gather data on parameters that are difficult to measure using quantitative techniques such as price perception or localisation of social media contact; and (2) confirm measurements recorded from the MySpeedTest in case results are skewed by outliers. The survey also collected some feedback about the general perception of mobile Internet. The survey basically answers the following questions:

- Preferred Internet connection type
- Availability of Wi-Fi access points
- Quality of service
- Amount of time spent on the Internet
- Main activities on mobile Internet
- Price and network reliability perception
- Localization of social media friends

Once the application was installed on the participants' phones, one issue encountered is that sometimes some of the phones were not collecting any data, whether it was for performance or usage. Those phones were therefore considered as "unresponsive" and were therefore removed from the statistics collected. Out of 23 users recruited, only 14 were active.

The primary aim was to gather data on mobile Internet usage while avoiding any interventions that might affect usage behaviour. Topping up users' mobile phones data as an incentive, would have biased usage patterns. Additionally, some participants did not feel that reimbursing the data used by the MySpeedTest application was a suitable incentive. Some other unresponsive participants said that their mobile phone "was off and they don't really use it as they had no airtime". Those participants were excluded from this study.

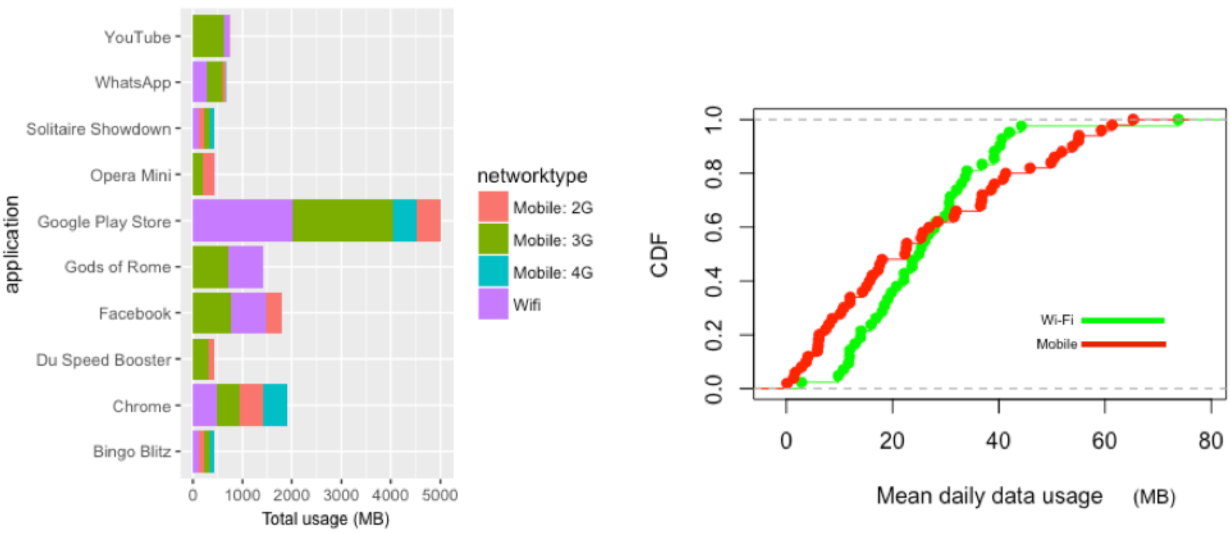
Finally, the MySpeedTest application separates mobile traffic into cellular and Wi-Fi. However, due to some limitations on the measurement platform, it is difficult to determine exactly to which access point the client phone has been connected. This limitation does not allow to separate “public Free Wi-Fi” from “paid Internet Café Wi-Fi”. The survey actually helps to fill this gap.

4.1.3 Empirical measurements and survey results

The study reveals interesting trends in the mobile data usage in the two township communities of interest. This general observation is that users in resource-constrained settings usually do not have the choice of connection type to access the Internet. The more privileged ones will have access to a Wi-Fi connection (if offered freely to the community). For others, they will have to rely on mobile data connectivity where the cost can be relatively prohibitive.

4.1.3.1 Most used applications and connection type

The amount of data sent and received by application was used as an approximate proxy for the “popularity” of the application; however, no distinction was made between applications running in the foreground versus in the background. Background processes are usually triggered by “administrative” applications such as software updates. However, if the device is infected with viruses and adware, those processes can also run in the background. Figure 4.3a shows the most used applications on Wi-Fi vs. cellular networks.



(a) Top 10 applications (b) Mean daily usage across all users

Figure 4.3: Breakdown in network connection type and total usage

Mobile 3G is a dominant connection type as shown in figure 4.3b. This observation differs from the comparative study of mobile usage between US and South African users, where Chen *et al.* found that South African users tend to use more Wi-Fi connections, whenever available, except for zero-rated services provided by their network carrier [76].

The study captured the mean daily usage in MB between Wi-Fi and cellular data across all users for the duration of the study and for 90% of the time, the amount of mobile traffic is slightly higher than Wi-Fi traffic, likely because most of the participants have much easier access to a mobile connection as opposed to a Wi-Fi connection. This trend can be confirmed after looking at the list of top ten applications and their breakdown in connection types. Mobile 3G surpassed Wi-Fi on its own and was far more popular than 2G or 4G, as well.

The three most used applications are Google Play Store, used to install new applications, followed by Facebook and Chrome. Having Google Play Store on top of the list is not surprising at all. Users tend to install new applications frequently, and updates are downloaded automatically in a background process. From discussions with the users, many are unaware that this is the default behaviour of their phones and that they should disable updates on mobile data if they want to save on their mobile data usage.

It was found that a large amount of data is used over cellular networks for applications installation and update. Some functions such as data backup to the cloud are done in the background. Also, most of the applications installed will also require regular updates, which will ultimately rely on an Internet connection. Application updates are made available on the Google Play Store and smartphones are automatically synchronised to pull the latest updates. With a median number of 39 applications per phone, if the update action is multiplied by thousands of phones in a community, the actual spending of data doing the same task can become a huge amount i.e. by updating the same set of applications. The idea ultimately, would be to find a solution that allows users to update their phones, without consuming Internet traffic, per se. If phone updates can be predicted and made available on local caches, not only will the updates be faster, but it will also be less costly. Newer Android versions by default perform apps update on Wi-Fi only, but unfortunately, users in low-resource settings do not necessarily have access to the latest versions.

It is also interesting to note that although there is no consolidation into Facebook as previously reported in Kenya [78], many of the most used applications are either games or social media. Although the demographic sample consists of 50% students, which could explain the reason behind the high prevalence of games, the survey results also indicated that one of the motivating factors of mobile usage in those two townships is entertainment. As Chirumimalla *et al.* proposed in their paper on "non-productive" activities and desires, the need to have fun and the need for entertainment in one's life is a central developmental aspect [123]. More research is needed to better understand these phenomena.

The bar chart in Figure 4.4a reveals an interesting trend in the Internet usage for gaming applications. Besides, Google Play Store, Facebook and Chrome, popular applications include Hidden City, Gods of Rome, and Bingo Blitz, which are most popular on the school students' mobile phones. In the future, it might be interesting to make a study of mobile phone usage for games and how gaming behaviour affects mobile data usage for people living in those communities. It is interesting to note that, bandwidth greedy applications such as Instagram and YouTube are not very popular both on mobile data and Wi-Fi, as opposed to the current situation with richer demographics, for example, in the USA, YouTube is the second most used application after Facebook [124].

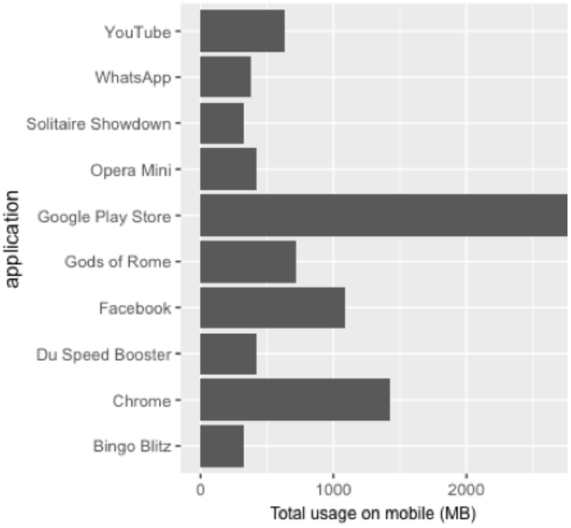
As expected, there was a big difference in the usage patterns for those with access to Wi-Fi. Google Play Store still tops overall usage, but it can be found that Chrome is much more utilised on 3G than on Wi-Fi. This result suggests that users tend to spend more time browsing either on news or entertainment, as found in the survey in Section 4.1.3.4. Interestingly, there was no usage of Opera Mini on Wi-Fi. Opera Mini is usually used to save up bandwidth especially if users are running on limited data bundles. Most probably, Opera Mini is the default browser on some of the participants phone.

4.1.3.2 Usage of zero-rated services

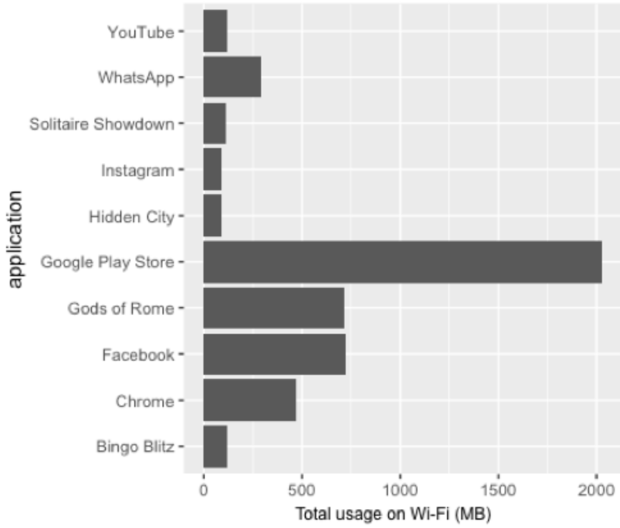
In a resource-constrained setting, one would expect to see a fierce adoption of zero-rated services. However, this study demonstrated that it is not always the case. It was found that users have a bad perception of zero-rated services, especially the Free Basics[7] service from Facebook. The fact that Free Basics does not allow users to see pictures and videos does not make the product very attractive. Users actually prefer using "paid" version of Facebook instead of using a "half-cooked" service as explained in Chapter 6.

It was also found that some users would rather use their current subscription of pre-paid mobile data instead of switching onto another network, where zero-rates apply for specific services. A recent study from the Alliance for Affordable Internet

[7]Free Basics Initiative, last accessed on 2016-12-20, https://connectivity.fb.com/free-basics/



(a) Mobile



(b) Wi-Fi

Figure 4.4: Top 10 applications

(A4AI) also confirms the findings[125]. They interviewed more than 8000 mobile users across eight countries and found the following:

- Zero-rating did not bring most mobile Internet users online for the first time
- Users typically combine data plans to suit their connectivity needs
- Public Wi-Fi is the primary means of connection for one in five users
- The vast majority of users (82%) prefer access to the full Internet with time or data limitations, if restrictions are imposed.

Currently, mobile operators in South Africa offer three zero-rated services: Whatsapp (USD 0.30 monthly), Free Basics (including Facebook), and Wikipedia Zero (freely accessible using Opera Mini). From the survey gathered, none of the participants uses Wikipedia Zero or Facebook on Free Basics. Figure 4.5 shows that Whatsapp is very popular on 3G, irrespective of the mobile operator. Vodacom has the largest share of Whatsapp paid data traffic, compared to Cell-C and MTN. The data suggests that Cell-C does not appear to offer a big enough incentive to induce subscribers to switch to their network with zero-rated Whatsapp service, but it would need a more detailed study to confirm this observation. There is currently vigorous debate around the provisioning of "free" services from Over-The-Top (OTT) providers, as it raises questions on anti-competitive practices as well as concerns on net neutrality [99].

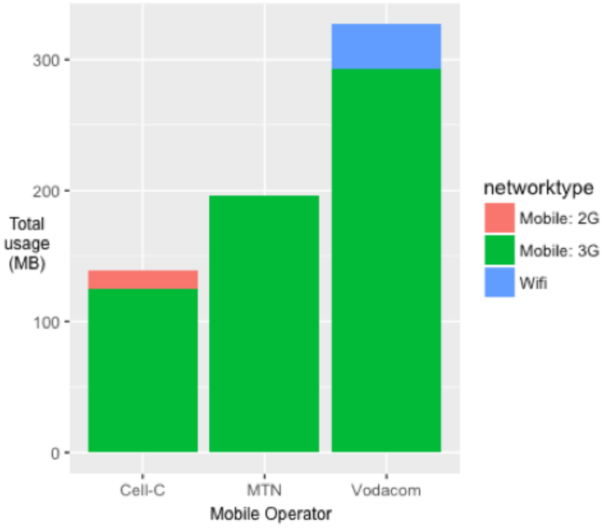


Figure 4.5: Whatsapp traffic by operators

4.1.3.3 File sharing and local traffic

To separate mobile data from local file sharing traffic, the usage of the *ShareIt* application was not included. However, it is interesting to note that 12 out the 14 users were actively exchanging data with their peers using the local file sharing application over Wi-Fi Direct, which enables easy peer-to-peer connectivity. It is much cheaper and faster to share large files locally rather than using an online file sharing service. This finding confirms what Smyth *et al.* found in their qualitative measurement study on mobile media sharing in urban India [126]. More recently, O'Neil *et al.* explain how file sharing has become a culture part of entertainment in their study of mobile sharing in lower-middle-class Bangalore [127]. This confirms trends found in the study.

Facebook and Whatsapp are two very popular applications that consume the biggest amount of mobile data, after Google Play Store and Chrome. It was also found that for a typical user, most of their social media friends are located roughly in the same locality [128]. Therefore, traffic destined for the same place, usually has to travel the world, over expensive links before being sent back to the user living in the same vicinity. A novel approach would be to find a mechanism that can effectively keep local traffic local.

4.1.3.4 Feedback from survey and interviews

The 14 participants were individually surveyed and their informal feedback were recorded on the survey questions, as well. Table 4.3 contains some snippets from interviewees on specific questions related to pricing, quality of service and social media practices.

As expected, all of the devices used were smartphones, with 3 out of 14 participants having an additional device such as a tablet that they use to access the Internet. None of the participants has a broadband connection at home, which is not surprising as the deployment of ADSL lines or fibre to the home (FTTH) is not a priority for broadband providers in those areas. Additionally, none of the participants has a mobile data contract plan; all of the users used prepaid data bundles, which also represents the main type of expenditure (78.6%), as opposed to phone calls (11%).

Cellular networks are by far the most used means of Internet connectivity in Ocean View and Masiphumelele. All of the respondents use their capped mobile data to access the Internet on a regular basis. Those who are working in the NGO Park benefit from the free Wi-Fi (not public) installed in there. Four respondents over 14 claimed they have used it. It might be the case that even though the participants have access to free Wi-Fi, they do not necessarily use it, as some of them have access to the Internet on their workstations. Seven out of 14 respondents said they do not have access to a Wi-Fi connection, whether paid or free. The students in Ocean View indeed have no other means of accessing the Internet aside from their mobile phones.

Vodacom is the most popular network (6 out of 14), followed by MTN (5 out of 14) and Cell-C (3 out of 14). Almost all the four Cell-C users subscribed to the monthly USD 0.30 unlimited Whatsapp bundle and claimed to have used the Free Basics service at least once. Those two "zero-rated" services are behind the popularity of this mobile service provider.

In terms of application usage, social media platforms are the most popular. Facebook and Whatsapp top the list followed by YouTube, Gmail, and games. One application that is also very ubiquitous is ShareIt[8], a peer-to-peer file sharing application. A few participants (2 out of 14) also mentioned using Opera Mini to browse the Internet. Opera Mini reduces the amount of data transferred by compressing images before they actually reach the mobile phones.

The coverage of mobile data networks and its reliability are both considered "rather fair", although some participants argued that sometimes the "connection is bad" and they had to move to other places to get a better connection. 9 out of 14 participants are opposed to "paying more", even if they would benefit from a better service. 6 out of 14 users argued that they are not quite satisfied with the current

[8]ShareIt does not need data connectivity, as files are transferred to peers using the ad-hoc mode of the phone wireless interface. ShareIt, last accessed on 2021-04-20, https://www.ushareit.com/

level of service provided by their mobile network operator for multiple reasons, price being one of the main reasons. Indeed, almost 9 out of 14 users believe the price of mobile data connectivity is not affordable and is the main reason that discourages them to use their phone to access the Internet. Out of the 14 interviewees, 7 users will typically spend between 3 to 6 USD monthly, 5 will spend between 1 to 3 USD and the remaining 2 spend between 6 to 12 USD. Finally, 9 users agree that keeping track of mobile data expenditure is sometimes problematic, which is consistent with the findings of previous studies [74, 75].

In terms of social media practices, most of the respondents are very active on a variety of social media platforms. The study has tried to understand their interactions with their social media friends; one notable aspect is "locality" . 50% of respondents say that they have at least 200 social media friends with 85.7% of them living in the same locality (0 to 10 km), 14.3% living in neighbouring communities. Another important aspect to understand was how "nomadic" cellphone users are between the two township communities studied. It was found that there are some movements, such as students from Masiphumelele going to school in Ocean View, or people from Ocean View going to work in Masiphumelele. Four out the seven students said that they move at least once or twice in week, the remaining three students move on a daily basis. More than 60% of the users would use their mobile phone to access the Internet outside of their home when visiting neighbouring places.

4.2 Characterising Internet traffic usage in a community network

Over the years, the Internet has also moved from being primarily a repository of information, to a place of services and communication. The many chat services (e.g. WhatsApp, Facebook Messenger, Line, WeChat) and social media (e.g. Twitter, Facebook) serve as ways for people to connect to one another, for entertainment, business, and social representation [78, 77]. In this there is often a locality of interest - stronger and more frequent connections are with people in your immediate vicinity [112]. Yet for those at the edge of the Internet, in its most expensive regions, users pay a premium to send these messages around the world just so they can arrive on the phone of a friend across the street explained in the next chapter 5.

There are of course ways around this. SquidProxy[9] was one of the earliest tools for cache-sharing, reducing the inefficiencies associated with many people being interested

[9]Squid Proxy, last accessed in 2021-04-05, http://www.squid-cache.org/

Table 4.3: Selected interviewees informal answers

	Answer
P1	*There is no free Wi-Fi at the library, only desktop access. I play games that do not consume data but the games come with lot of ads, so I don't know if the ads are consuming my data. I tend to avoid YouTube at all. I usually spend 10-15min every time I use my mobile Internet, to download something quickly and watch later offline. I access Facebook on a daily basis at least 30 minutes a day. Only certain areas have 3G connectivity. I use Free Basics for Facebook, but the issue is that there are images and videos, so it's not worth it. I prefer to pay data and use the proper Facebook. I sometimes use Whatsapp to call my friend on 3G, but sometimes connection isn't that great.*
P3	*There is no other means of Internet connection besides mobile 3G. I spend most of my money on buying data bundles for sending Whatsapp messaging. YouTube I access sometimes but it is very data-intensive, I try not to use it. I use ShareIt to share applications and videos with my friends.*
P8	*I spend sometimes R5 or R10 each time I recharge and I can recharge up to 5 times per week. I buy the R5 monthly Whatsapp bundle on Cell-c but I cannot do Whatsapp calling, only messages, images etc. I sometimes use Free Basics but I don't like to use Facebook on this as no videos/images available, it is also very slow. I have more than 1000 friends on Facebook, some of them living in neighbouring townships but most of them live in Masiphumelele. If Internet was unlimited, I would look for more information on school subjects, see how I can download new applications, videos. I can use data-intensive apps such as Skype or Google maps to locate things, while moving around. Learn new things by watching online videos.*
P12	*I have Internet access at work, so I don't use that much of data, but during weekend I use data and it goes fast. My kids would watch YouTube videos and will burn all my data bundle and airtime so I have trouble keeping an eye on my consumption.*

in the same web content. Services such as FireChat enable peer-to-peer chat via ad-hoc connections [129]. OwnCloud[10] and NextCloud[11] support local file hosting. However, these services are scattered and primarily used by technology experts. How to enable communities, especially in low-resource settings, to leverage these existing

[10]OwnCloud Cloud Storage, last accessed in 2021-04-05, https://owncloud.org/
[11]NextCloud Cloud Storage, last accessed in 2021-04-05, https://nextcloud.com/

services?

Through this initiative, this work experimented with ways to move communication back into communities, not just logically, but in terms of infrastructure as well. This was achieved by leveraging mesh Wi-Fi to enable a community-owned wireless network and by placing a server in the network to offer local services: file sharing, chat, social networking. The idea of this project is, in the long-run, to work with the community to develop new, community-specific services using a co-design approach. This study focuses on the initial months of the network deployment to understand the impact of providing a subsidised access to the Internet and the subsequent user behaviours online.

Following the survey on mobile Internet use, the data collected helped to design the *iNethi* platform as described in the next section.

4.2.1 iNethi Community Network

By virtue of their proximity to the end-users, Community Networks (CNs) [130] offer an ideal platform for low-latency services ideal content delivery, large file exchange, video streaming and real-time communication. The community, with the help of researchers, deployed *iNethi* which means the "net" in isiXhosa and which proposes a concept to "bridge the gap" between communities through ICT-enabled services such as social networking, instant messaging, e-reporting and participative democracy. iNethi also provides low-cost access to the Internet using a voucher system (USD 0.60 per GB) which is 15x cheaper than the average price of a 1GB mobile data package.

The iNethi network is administered by OVCOMM, a co-operative comprising of members depicting a cross-section of the community. The mandate of OVCOMM is to develop local content of the community that reflects the values, cultures, beliefs and shared heritage of the community that can be shared across the iNethi network. This is encapsulated in the vision of OVCOMM of participatory co-designing of services, i.e., working with the community to establish needs and norms of the community. Furthermore, it is the believe of OVCOMM that the iNethi Community Network becomes a key enabler and catalyst of sustainable access to the Internet and local services. It therefore has the potential to contribute critically to sustainable development within the community and its surrounding areas.

4.2.1.1 System architecture and network layout

The iNethi architecture shown in Figure 4.6 is designed around two needs: (a) Access to local content and services and (b) Access to the Internet through a radius authentication and accounting system.

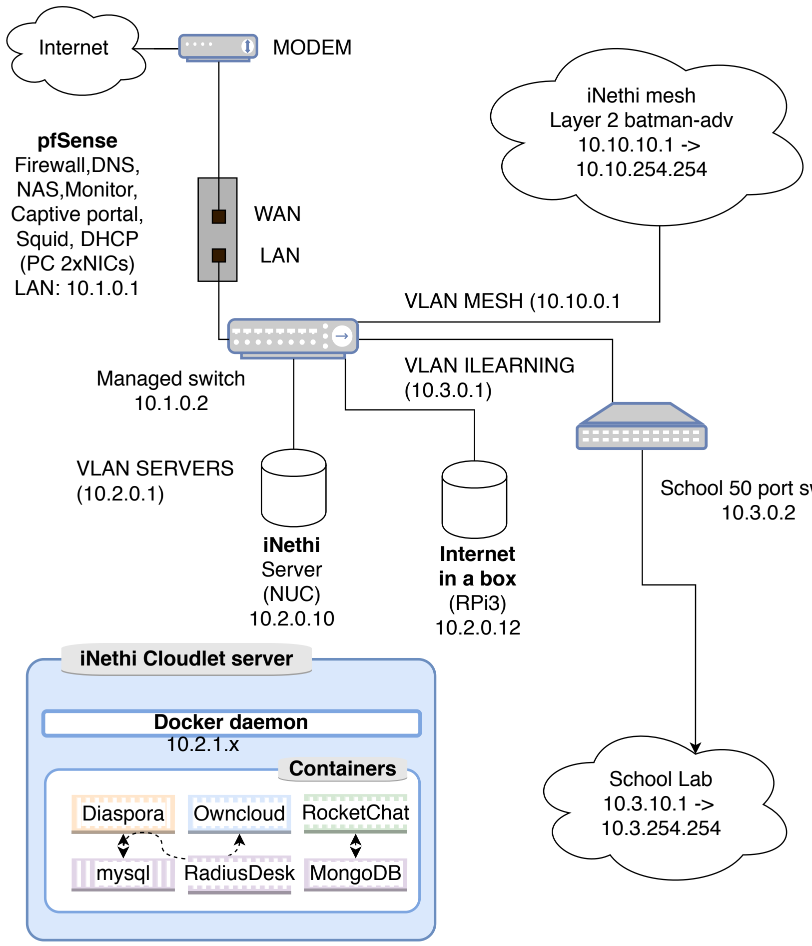


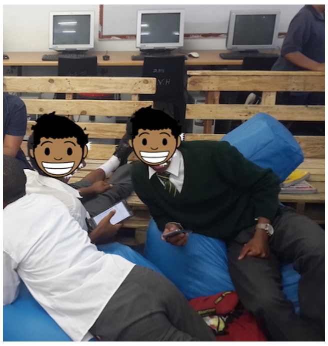
Figure 4.6: iNethi system architecture

The local network is split into VLANs through a managed switch. These VLANS are: (a) the LOCAL servers (b) the MESH network and (c) the SCHOOL network. All data were collected at the gateway. The Switch is connected to a pfSense Firewall[12] which manages the VLAN subnets. pfSense provides DNS and DHCP services for the network as well as a captive portal that authenticates users and carries out user accounting through a radius server. The domain *iNethi.net* was globally registered and by overriding the DNS lookup to point to the local servers, users in the local community were able access this domain. This setting also allowed users who travel outside the community to eventually use the same domain to access iNethi servers in other communities or on global servers. iNethi is equipped with a Radius server,

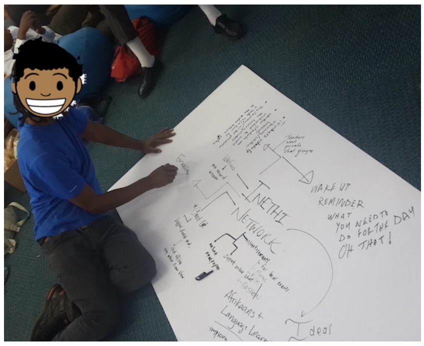
[12]pfSense Firewall, last accessed on 2021-04-19, https://www.pfsense.org

which provides services to manage users and create vouchers that are time or data capped.

The SCHOOL lab subnet connects all the desktop computers in the community High School lab as well as some mobile devices that are brought into the lab. The Mesh network subnet consists of all the mesh devices connecting homes and flats across the community.



(a) School lab with students accessing iNethi using their mobile phones



(b) A co-design workshop with students and community members

Figure 4.7: Pictures from the Ocean View High School Lab and from the participatory co-design workshop organised by researchers

Raspbian Stretch was flashed onto a 128GB microSD card which was connected to a Raspberry Pi 3B+. Internet-in-a-Box (IIAB) was installed by running an ansible curl script to modify variables within local_vars.yml and install a suite of over 20 server applications.

A few of the key applications[13] relevant to this project include:

- AWStats - AWStats is an open source Web analytics reporting tool, suitable for analyzing data from Internet services such as web, streaming media, mail, and FTP servers. AWStats parses and analyzes server log files, producing HTML reports.
- Kiwix - Kiwix is a free and open-source offline web engine
- Wordpress - WordPress is most associated with blogging (personal journaling) but supports other types of web content including more traditional mailing lists and forums, media galleries, and diverse plugins.
- Kolibri - Kolibri provides offline access to a wide range of quality, openly licensed educational content.

[13]Internet in a Box, last accessed 2021-02-10, http://wiki.laptop.org/go/IIAB/FAQ

Table 4.4: List of local services deployed on iNethi

Service	Host	IP
Inethi in a box (IIAB)	box.inethi.net	10.2.0.12
RocketChat	chat.inethi.net	10.2.1.11
Diaspora	diaspora.inethi.net	10.2.1.15
Home page	home.inethi.net	10.2.0.10
Owncloud	owncloud.inethi.net	10.2.1.13
Radius Voucher	radiusdesk.inethi.net	10.2.0.3
Splash page	splash.inethi.net	10.2.1.17

Upon installation of IIAB, the domain was set to *inethi.net* within the admin console, and the Raspberry Pi hotspot was disabled. 100GB of educational content was downloaded and transferred to the device using a USB flash drive. This content included Wikipedia in English and Afrikaans, TED talks, Wordpress was set as the default landing page in IIAB, which was edited to include information about iNethi and links to the various services and content.

Additional local content is hosted on a Linux server running docker containers as well as a Raspberry PI 3 with a 1TB SSD for running Internet in a Box. The local services (Rocketchat, Diaspora and Owncloud) are all accessed as web application and can run on a desktop computer or a mobile device (see Table 4.4). The services are hosted on Docker containers and each of these services is assigned a unique IP address as well as a unique subdomain, such as *chat.inethi.net* for Rocketchat, for each service on the pfSense DNS server. These specific services were chosen as they are effectively content-neutral and are alternatives of popular services - WhatsApp, Facebook and Dropbox - on the Internet.

Wi-Fi access to the OVCOMM network is provided through 9 WiFi mesh node spread across Ocean View (see Figure 4.8). The gateway node is at Ocean View high school. Internet access between November 2018 and December 2019 was provided through a Telkom ADSL line (8 Mbps downlink and 512 Kbps uplink). The current Internet link, installed in December 2019, has been sponsored by Sonic Wireless (10 Mbps downlink and 5 Mbps uplink). Sonic Wireless provide access through a series of 5 GHz wireless backhaul radios that connect to fibre approximately 10km away.

4.2.1.2 Economics

The OVCOMM Community network runs as a classic cooperative where members are the primary stakeholders and reap the benefits of a mix of income and access to

Figure 4.8: OVCOMM mesh network

services from the cooperative. The members also invest in the cooperative with their own resources in the form of time and labor.

This particular cooperative was bootstrapped using a grant from the University of Cape Town that provided 10 mesh nodes and the iNethi server as well as a year's Internet access in 2019. In 2020 a local ISP agreed to donate a 10 Mbps Internet link, all future growth of the Internet will come from the cooperative.

Income is generated from voucher sales. Currently vouchers are sold for R10 per GB (USD 0.60). Cooperative directors have uncapped Internet to their homes and cooperative members who host mesh radios at their house get some data sponsored for free. The 10 Mbps link can provide 3240 GB per month of data if the link was used continuously for a month. If at least 30% of this capacity being lost due to non-use at night and 20% of this capacity being used by the directors, this leaves 1620 GB to be sold in the form of vouchers (a potential income of USD 1000). A typical user spends approximately USD 3 per month (5GB per month) on data. On average this amount of data will be consumed by 324 users. Some of this income can be used to pay dividends to cooperative members and to invest in more radios to grow the network and upgrade the back-haul.

Table 4.5: PCAP files capture between Aug-2019 and Jan-2020

Location	**# of pcap files**	**Size (GB)**
Mesh	4815	1286
School	4815	604
Servers	4815	21
Total	**14445**	**1911**

4.2.2 Methodology

The traffic characterization of Internet usage in the iNethi network has been conducted using passive measurement techniques. The primary datasets are traffic logs collected at three different collection points, namely at the school, the mesh and at the server level. The Internet traffic data of the iNethi network was logged for a period spanning over 25 weeks from August 2019 to January 2020. Table 4.5 shows the amount of data and the number of pcap files captured. Each pcap file corresponds to 1-hour of traffic. All logs were captured on the pfSense firewall installed on the the edge routers at each location.

To conserve on storage space and to facilitate the traffic analysis, only two main datasets namely the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) conversation statistics and HTTP traffic logs from the pcap files were extracted. For this,*tshark*, which is the command-line interface for WireShark, was used. From the tshark conversation statistics, each line represents a connection between the client and the server as shown in table 4.6. The most relevant fields are the timestamp, source and destination IP and port, TCP and UDP payload size (in bytes), the duration of the connection.

By processing the logs local traffic going to the iNethi localised services and to the Internet, were categorised. To identify local traffic, the destination address (in the 10.2.X.X subnet) were filtered out, where local services such as Diaspora, RocketChat, Owncloud, etc are hosted (see table 4.4 for list of local services). Finally, features such as the destination FQDN, the request URI, number of hits, bytes transferred, etc. were extracted from the HTTP traffic dataset.

Table 4.6: Sample PCAP conversation statistics

date	location	protocol	src_ip	src_port	dest_ip	dest_port	download_bytes	upload_bytes	total_bytes	duration
26/08/2019 12:30	mesh	TCP	10.10.161.48	51388	10.10.0.1	8002	167894	13243	181137	3.6265
26/08/2019 12:30	mesh	TCP	10.10.173.219	32972	10.10.0.1	8002	190674	11152	201826	2.2383
08/08/2019 18:56	school	UDP	10.10.167.90	53153	10.10.0.1	53	409	78	487	0.0001
08/08/2019 18:56	servers	UDP	10.10.161.49	60232	10.10.0.1	53	329	88	417	0.0001

To summarise, this study focuses on a six months worth of Internet and local traffic with data captured from three main locations (the Mesh, the School and on the "Servers" hosting the local services). In total, this represents more than 35 million TCP connections and 13 million UDP connections to both local and external services.

4.2.3 Network usage analysis

This section presents the iNethi traffic measurements from the three collection points (mesh, school and servers). The collected data was grouped into three categories: local/external, upload/download and TCP/UDP for the three locations. “Local traffic” stands for traffic towards the set of local services and “external traffic” stands traffic going to the Internet. The idea is to compare outbound and inbound traffic to and from the Internet and within the local network, where access to the different services is zero-rated.

4.2.3.1 Local and external download traffic overview

Figure 4.9 shows a graph of the download traffic for both local and external services. First, it can be observed that download from external service is almost 50x more than local service, as quite understandably, users are generally more interested in "popular" service than in local educational material, even though they are zero-rated. Nevertheless, over the 6-month period, there are some download activities on the local services, which tends to show that local services are used.

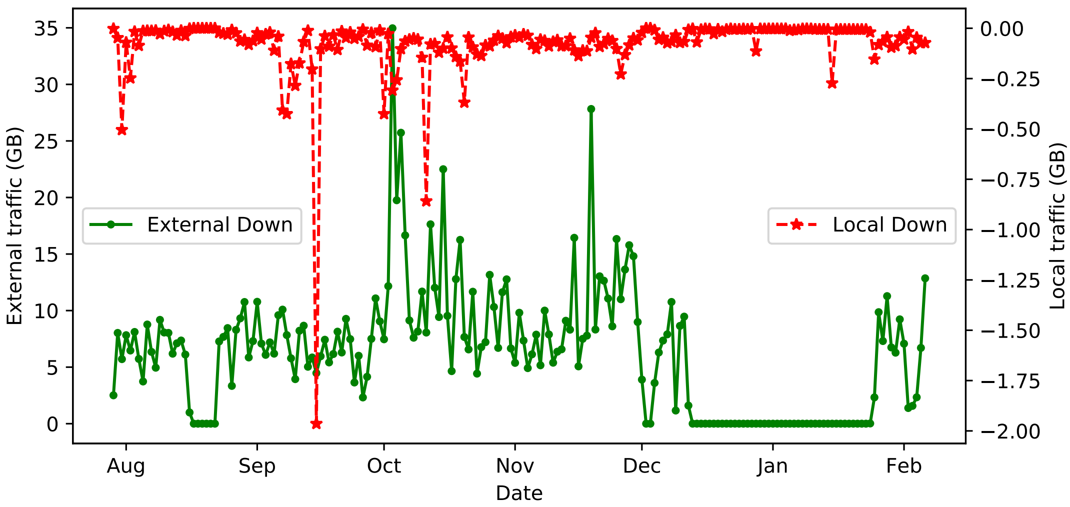


Figure 4.9: Time series of Down-link daily throughput. Green line represents the download traffic from external (left y-axis) while the red line represents download traffic from local servers (note the different scale used for local-download is inverted - refer to right y-axis)

By further breaking down the traffic between the locations where Internet and local services are accessed, it can be observed that 25% of the time there was no network availability. This was due to a very unreliable ADSL network and very poor response time from the operator when asked to have the issue repaired. Table 4.7 provides some details on the different downtime events and the associated causes. It must be noted that since Q1 2019, South Africa has been going through a major energy crisis[14], affecting Internet connectivity at many different levels. The dip in November/December was due to an unreliable backhaul link.

Table 4.7: List of issues which caused downtime in the network

Date	Issue/Diagnosis
26-Aug	NUC off, no space left on Radius Desk Raspberry Pi
08-Oct	Switch over to new voucher system
04-Dec	Network off (frequent load shedding)
18-Dec	a) Telkom account suspended after 1 year b) Repeated load shedding causing Radius Desk
24-Jan	Sonic ISP link up
08-Feb	pfSense firewall hard drive full

[14]South Africa Energy Crisis, last accessed on 2021-01-20, https://en.wikipedia.org/wiki/South_African_energy_crisis

In order to the understand the download pattern over a week, download data between Oct-14 and Oct-21 was analysed. Figures 4.10 and 4.11 provides a graphical overview of a typical weekly download traffic for both local and external services. As it can be seen, the local download traffic is almost negligible as compared to Internet traffic. As it is expected in most user-based web traffic analysis, the network traffic shows a strong diurnal pattern, with peaks at around 8am, 2pm and 8pm. It is interesting to observe that unlike previous studies where traffic drop during weekends [112], there was some amount of activity between Saturday afternoon and Sunday morning. This shows that students and users in the community in general rely on the iNethi network for Saturday night entertainment activities - a facility which they could not enjoy before the setup of the mesh network. This pattern was also noticed by Johnson *et al.* in the Macha Network in Zambia [112].

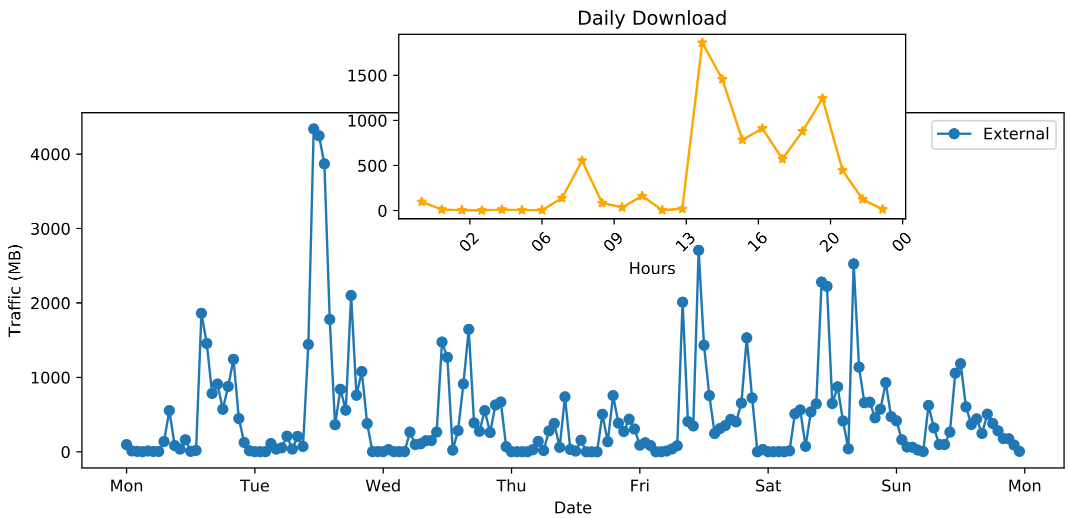


Figure 4.10: Daily/Weekly traffic to external services

With regards to local services, the download traffic pattern is less *spiky*. This can be explained by the fact that local services are sparingly used. But the local services download traffic also follows a diurnal pattern with a peak at 2pm. This peak corresponds to heightened usage during school hours, where students would spend time on the local Wikipedia and offline educational videos provided for free.

Finally, it is interesting to note that from Figure 4.12 UDP represents a considerable amount of traffic on the whole. Usually, UDP traffic is mostly related to DNS queries and IP multicast services, but the ratio of TCP over UDP traffic is 4:1. During the period of capture (Aug-Jan), the total TCP traffic amounts to 972 GB and UDP traffic to 240 GB. Most probably a major part of the UDP traffic is due to the

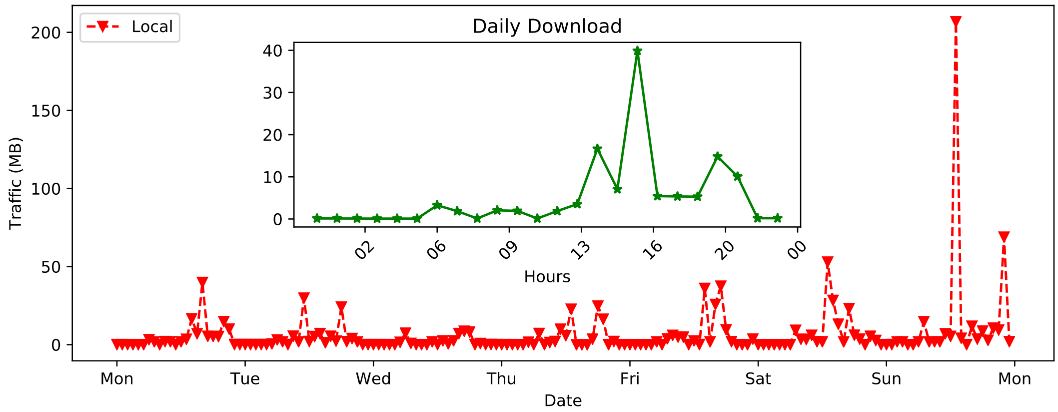


Figure 4.11: Local Services

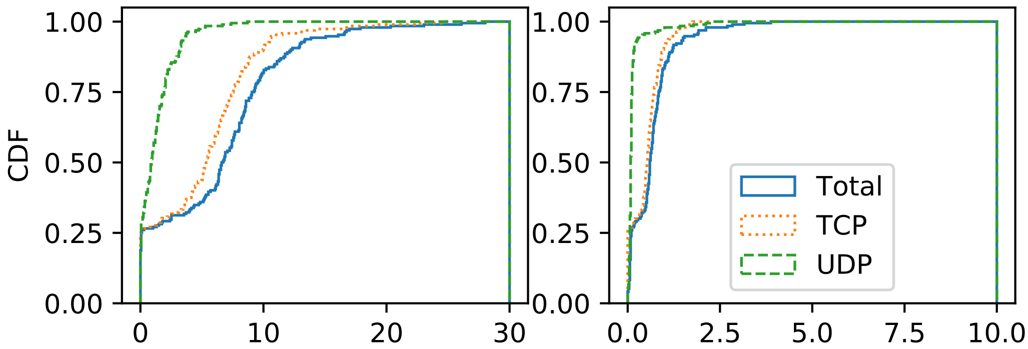


Figure 4.12: CDF of download vs upload traffic for TCP and UDP traffic

heavy use of Google Chrome as main browser. Google Chrome operates QUIC which is a UDP-based secure transport protocol. QUIC runs by default in all Chromium-based browser as from version 29, circa 2013. It can be observed from Figure 4.13 a strong correlation between upload and download, meaning that users in both mesh and at the school have been consuming and also generating content in a relatively proportional way.

4.2.3.2 Web traffic analysis

This study used the same 6-month worth of packet capture files to extract HTTP features. Some of the features are the source and destination IP and port numbers, the request URI, the request type (GET/POST), the user-agent, the amount of bytes transferred and the hostname. A first-hand analysis of the HTTP user-agents was performed and it was found that a majority of users (66%) are using Android devices, out of which 23% are using Android 7.0 (release in 2016). The most used browser is

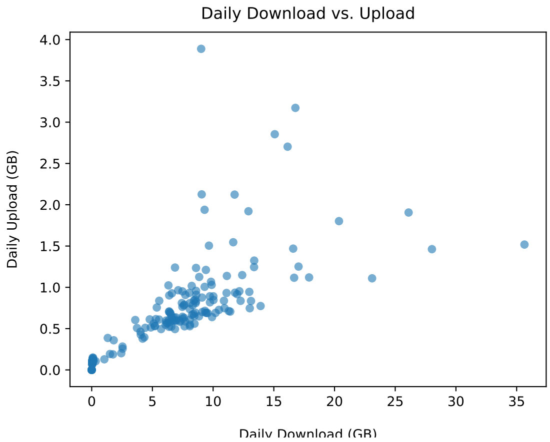


Figure 4.13: 0.74 Pearson's coefficient of correlation between upload and download

by far Chrome Mobile at 74%, followed by Opera, Internet Explorer, etc making up the remaining 26%.

In Figures 4.14 and 4.15, the most used services (local and external) from the school and the mesh are characterised. Surprisingly, Avast, which is an anti-virus software, is consuming lot of Internet traffic (up to 10 GB for the school) and (4GB for the mesh). Obviously, not all users are aware of anti-virus software updates and the fact that this activity is consuming a considerable amount of their data package/voucher. A lot of updates were also targeting other platforms namely towards Microsoft, Apple, etc.

4.3 Limitations

While this study provides a detailed local view of Internet usage in a low-resource setting, it is however limited in terms of number subjects studied and locations where the study was carried out. The sample used to conduct the mobile usage study is small and limited to one specific township only and the passive measurements were taken from one community network only.

Nevertheless, the main contribution of this chapter is the methodology used to study the Internet usage. The mixed-method technique which includes both active and passive measurements as well as qualitative surveys was tested and proved it could also work in other locations. Such a study can therefore be scaled to cover multiple low-resource areas and other community networks in the African region. However, large scale studies do come with their own challenges and the following options can

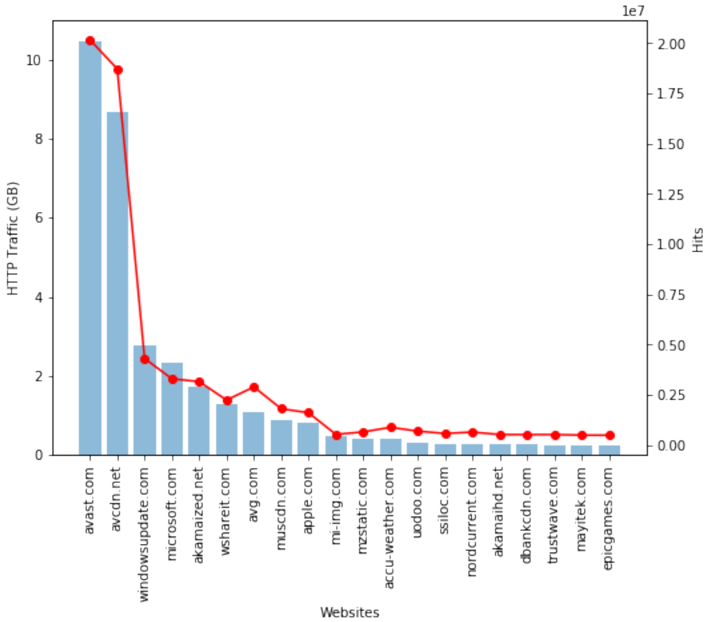


Figure 4.14: School traffic

be envisaged:

1. Build agreements with existing community networks providing both local and Internet access to users living in low-resource settings.

2. Users should be made aware of the planned measurements and their consent should be taken upon registration to the network.

3. Instead of deploying mobile measurement apps, other techniques such as light-weight web measurements could be explored.

4. Users of the community networks could be reached out for online surveys through their mobile device either via push notifications or via the splash page during login.

5. To increase uptake for the online surveys and voluntary measurements campaign, explanatory videos should be created and pushed to the subjects, together with incentives such as a lottery or vouchers for Internet access.

4.4 Conclusion

This chapter presented a study of mobile data usage in South African townships, using a combination of quantitative data of application usage from mobile devices

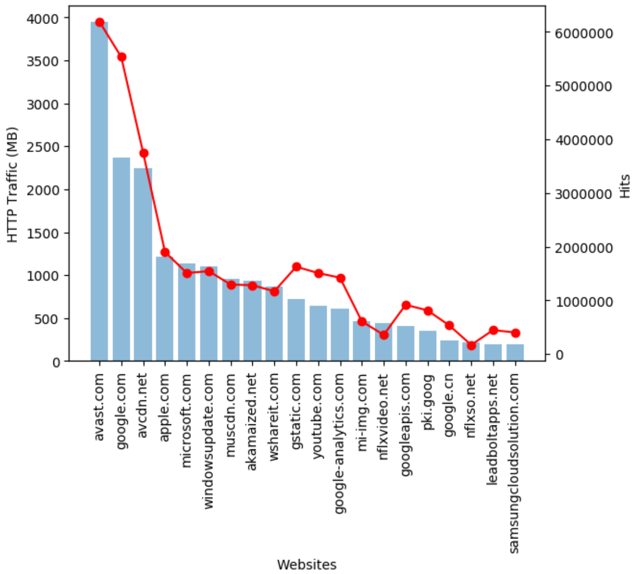


Figure 4.15: Mesh traffic

and qualitative survey data. It was particularly important to understand both how people use mobile data and the economic implications of user behaviour in resource- and income-constrained settings. The aim was to gather trends that could influence the design of applications and network architectures that are more cognisant of the high data costs relative to other means of Internet access (e.g., public Wi-Fi).

It was found that, in contrast to wealthier communities with better resources, township users use cellular data networks relatively more than Wi-Fi networks, both in general and for specific purposes such as application updates. Qualitative survey results suggest that this behaviour may be due to the relative inaccessibility of public Wi-Fi in townships. These findings suggested that much work remains, both in the design of mobile applications and network architectures to better optimise cellular data usage and in thinking about how to design communities to increase the accessibility of lower-cost access alternatives, such as public Wi-Fi.

Furthermore, this chapter presented a network traffic characterisation study of a community offering access to both local and external services, based on 6-month of data collected at two main locations (the school and the mesh). The study analysed the traffic profile, transfer sizes, throughput, etc and identified several trends in the time series data, such as diurnal patterns, (in)consistency from day to day, and modified usage patterns on weekends. It was found that the community network was being mostly used as a means of entertainment. On many occasions, the reliability of the network was affected mainly due to links going down and load-shedding. The web traffic analysis has also shown interesting pattern, whereby, a lot of data was being consumed by background services such as anti-virus software, phone and PC updates. Users buying vouchers were actually unaware that a considerable amount of data is lost in software updates. In the future, iNethi administrators should consider zero-rating software updates.

Finally, the data captured showed some skewed distributions with high variability (e.g., transfer sizes, throughput), and heavy-tails (e.g., connection duration, transfer sizes). It was also seen that the use of localised services, though consistent, remained relatively low as compared to the use of Internet-related services. To make localised content and services more attractive, there is a need to produce *relevant local content* (e.g. locally produced music and videos) that will help promote the usage of zero-rated local services, instead of using bandwidth-greedy applications such as YouTube.

Chapter 5

Accessing Local Content in Africa

This chapter adopts a content use, hosting and distribution perspective to assess the level of Internet development in Africa. It does so by providing empirical evidence on the important issues of local content by adopting an Internet measurements perspective. The research identifies bottlenecks related to content hosting and performance issues to access local content from Africa and provides points of policy recommendations on how to improve local web hosting across the continent. As per the OECD report on local content [23] , local content can come in different types and forms but they are all characterised by (1) the locality of interest i.e. the content should be relevant to the local community, (2) their timeliness i.e. people tend to consume content which are recent and contemporary. Based on the above two criteria, the thesis explored two main proxies for local content namely: African local news websites and public sector websites.

5.1 Case study I: Local news websites

5.1.1 Research Questions

This section studies the use, hosting and distribution of local news websites in Africa. More specifically, the following key questions are empirically answered:

1. Where is local African news websites hosted?
2. How is content hosted in Africa?
3. What routes are used to access locally hosted content?
4. What is the latency for content hosted in various regions?

In answering these key research questions, this study makes three contributions: First, it offers a discussion on challenges related to usage, hosting, distribution and accessing of local content in Africa. Secondly, this study makes publicly available[1] measurement data on the web content infrastructure in Africa, and at the same time, it illustrates the factors affecting performance when accessing Africa's digital content. The third contribution of this study is the provision of specific policy recommendation points on how to improve Internet adoption and infrastructure performance from a content perspective. To achieve this, the study undertakes an active Internet measurements campaign to characterise the latencies and to geolocate web servers and routes used for Africa's online content, focussing on local news websites in each country.

5.1.2 Research methods and data sources

5.1.2.1 African local news websites

Internet measurements were conducted to gather information regarding where Africa's web content is hosted, as well as to assess the associated performance and cost implications. The first task was, therefore, to identify websites that would be considered representative of Africa's local web content. In this study, Africa's web content is defined as content that is primarily generated and consumed within each African country. One way of sampling websites is through listings of the most popular websites as ranked by "webometric" sites, the most popular one being the Alexa Top [2]. The analysis of the Alexa top-50 sites for African countries showed that lists were largely dominated by non-African sites. It was also noted that some local websites that are known to be very popular in some African countries were missing as top websites, thereby casting some doubts on the representativeness of the webometrics for Africa. It was decided, therefore, to study local news and media websites, which by definition constitute a significant body of local content in Africa. A list of local news websites made for every African country was compiled from ABYZ News Links [3], an online directory of links to online news sources from around the world organised on a geographical basis. In contrast, the ABYZ News Links directory does not rank the sites, but rather attempts to list all the prominent media sites for each country. This study thus explores the hosting choices and performance associated with a large sample of more than 1000 local news websites as **a proxy for local content** (summarised in Table 5.1).

[1] Africa Content Study, accessed on 2021-02-21, https://github.com/AFRINIC-Labs/content-africa-study

[2] Most popular websites list, last accessed on 2021-03-12, https://www.alexa.com/topsites

[3] Available at the following link: http://www.abyznewslinks.com/

5.1.2.2 Geolocation

Second, to respond to the question of whether local news websites are locally hosted within their countries or not, traceroute data was analysed to determine the networks that host each of the measured websites, as well as the networks through which traffic flows between the websites and the measurement vantage points. Subsequently, the geographical location of each web-hosting server was determined. MaxMind[4] geolocation database was used to obtain the network information, which includes the networks' Autonomous System Numbers (ASNs) and network names. The geolocation database was also used to identify the countries related to each IP in the dataset, both the websites' web servers and routers along the paths to the websites. The country-level geolocation was preferred as it has been shown to have relatively higher accuracy compared to city-level geolocation [131, 132]. It is worthy to point out the known limitations with geolocation databases; it is likely that discrepancies within MaxMind introduce noise to the data analysis. However, as stated above, the analysis in this study is limited to country-level geolocation to minimise the impact of database inaccuracies.

5.1.2.3 Traceroute dataset

From each country and for each website, a maximum of 10 probes were selected and used to launch traceroute packets to each of the country's websites. The traceroute measurements were repeated over a five-day period, resulting in about 19,299 successfully measurements between the probes and the websites. Each traceroute measurement returns three final hop Round-Trip Times (RTTs), meaning that in total, there were 57,897 end-to-end RTTs. A traceroute measurement is considered successful if an IP route can be determined from the source to the web-hosting network, thereby also being able to reveal a delay estimate to the website. Each successful measurement contains the IP address of a website's hosting server, a series of IP hops from the vantage point up the server, as well as the delays (RTT) at each hop (router). Also, each traceroute result is made up of multiple records, one record for each of the multiple hops on the path. Consequently, the final dataset was made up of 256,654 records, with each record comprising source and destination addresses, as well as the IP hop and RTT from the source to that hop.

[4] https://www.maxmind.com/en/geoip2-country-database

Table 5.1: Number of news websites measured per country

Country	**# of news website**	**Measurements Completed**	**RTT Samples**
Burundi	12	102	306
Benin	23	580	1740
Botswana	13	160	480
Congo DRC	22	211	633
Congo	8	40	120
Côte d'Ivoire	22	172	516
Cameroon	28	823	2469
Cabo Verde	9	45	135
Algeria	100	947	2841
Egypt	26	181	543
Ethiopia	27	257	771
Ghana	44	547	1641
Gambia	10	98	294
Kenya	23	767	2301
Lesotho	5	25	75
Morocco	37	619	1857
Madagascar	10	177	531
Mauritius	10	341	1023
Malawi	19	368	1104
Mozambique	7	234	702
Namibia	15	148	444
Nigeria	176	1381	4143
Réunion	5	236	708
Rwanda	8	38	114
Seychelles	4	32	96
Sudan	11	107	321
Senegal	21	308	924
South Sudan	13	64	192
Eswatini	3	14	42
Togo	18	651	1953
Tunisia	19	801	2403
Tanzania	18	662	1986
Uganda	31	564	1692
South Africa	126	5284	15852
Zambia	38	465	1395
Zimbabwe	78	1495	4485
Total	**1039**	**19299**	**57897**

5.1.3 Data analysis

5.1.3.1 Geolocation of African news content hosting

The hosting and geolocation analysis indicates that about 85% of the news websites are hosted outside the countries in which they belong, i.e. the website is owned and it is local to one country, but is hosted in another country. This is, hereafter, referred to as remote hosting. Analysis of remotely hosted websites reveals that most of them are hosted in Europe and the US.

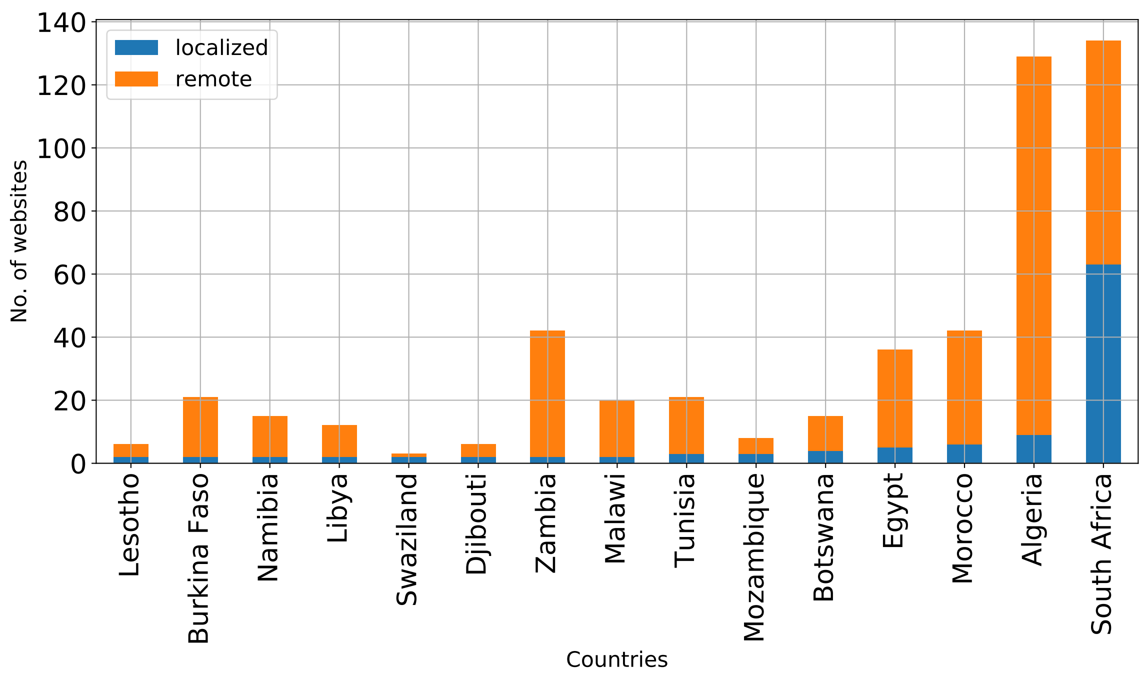


Figure 5.1: Number of websites per country local vs remote

Figure 5.1 below shows a country-level distribution of locally hosted websites versus remotely hosted. Almost all the countries in the sample have less than 30% of their websites hosted locally, and about half of all the countries have less than 10% local hosting. South Africa (ZA) appears to have a high percentage of local hosting with 46%.

The US takes the lion's share in hosting African content, with about 58% of all the websites being hosted by American companies. Within Africa, South Africa leads in the content hosting business, hosting about 14% of all of Africa's remotely hosted news websites (i.e. minus those that belong to South Africa). The rest of the websites, about 20% are hosted in various countries in Europe (notably, 9% in France, 4% in Germany, and 3% in Great Britain). This signals low participation of the continent's companies in content hosting. Most of the websites that were observed to be hosted within Africa were based in South Africa, while the majority of the rest are hosted in either the US or Europe.

Additionally, about 45% of all the IP hops (i.e. Internet path) for accessing African websites, from African countries, traversed outside African clients' home countries. Internet packets travel mostly through US networks, and about 23% pass through European networks. South Africa takes about 8% of all IP hops for traffic traversing to other African countries.

5.1.3.2 Network-level analysis of Africa's news sites

Similar to the geolocation analysis, network-level analysis shows that most of the websites are hosted by foreign companies. Taking into consideration all the sampled African news websites, Cloudflare Inc (US) takes the biggest share of the market, hosting about 22% of the websites. Following in the far distance is OVH SAS (France) with 8%, OPTINET (South Africa) at 6%, Google LLC and GoDaddy.com (both US) at 5% each, and Unified Layer (US) at 4%, and HETZNER (South Africa) at 3%.

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With regards to the hosting market share, i.e. if only remotely hosted websites are considered, Cloudflare take an even bigger share of 26%, followed by OVH SAS (9%), Google LLC (6%), GoDaddy.com (5%) and Unified Layer (5%). What is interesting to note is that the leading providers for Africa's remotely hosted news websites are largely based on Cloud infrastructure and make use of content distribution networks.

5.1.3.3 Delay Analysis (Round Trip Times) to access locally and remotely hosted content

Analysis of RTTs when accessing the websites from each of the countries shows significant RTT differences between locally hosted websites and those remotely hosted. The maps in Figure 5.2 below highlights country-level RTT differences for local and remote hosting. The median RTTs for locally hosted websites is about 50ms, whereas for remotely hosted websites, the median RTTs range between 100ms and 300ms.

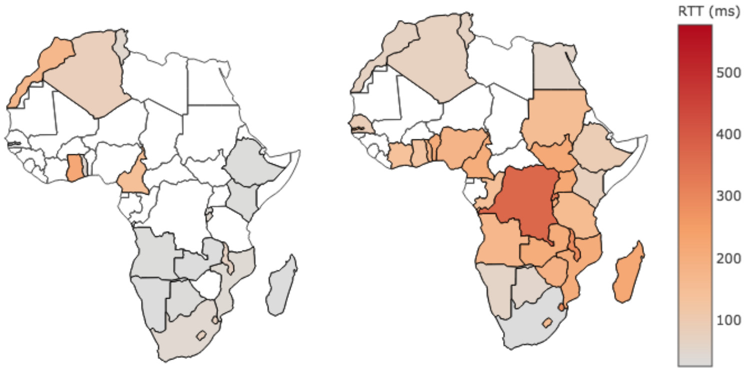


Figure 5.2: National median RTT comparing locally (left) vs remotely (right) hosted content

The range of median RTTs shows significant differences between countries for websites hosted within each country. The study found out that out of the 22 countries where local hosting performance was measured, 16 countries registered local median RTTs of less than 50ms, while the other six countries (Angola, Malawi, Lesotho, Algeria, Cameroon, Morocco, and Ghana) had local median RTTs ranging between 50ms and 200ms. The analysis shows that in some countries, the median RTTs for locally hosted websites is higher than for websites that are remotely hosted. Examples include Ghana, where the median RTT for locally hosted websites was found to be 205ms, whereas for remote websites, the median RTT was 127ms; and Morocco, where the local median RTT was 152ms against a remote median RTT of 68ms. RTTs of over 100ms for locally hosted websites could suggest circuitous paths, where locally hosted websites are accessed through Internet paths that traverse other countries.

This further indicates a lack of peering, where interconnections between local networks are done through networks in remote countries. In Ghana for example, one probe reached the locally hosted `www.ghana.gov.gh` by traversing remote networks, chronologically through Ghana, South Africa, UK, South Africa, and Ghana, resulting in a delay of 380 ms. Similarly, in Morocco, a locally hosted website `www.leseco.ma` was reached by a probe in Morocco by traversing four networks, first in Morocco, then France, Ireland, Canada, and back to Morocco, experiencing a delay of 160ms. These examples illustrate that in the absence of local peering, local hosting of websites tends to force much more circuitous routes for accessing the content than when the websites are in foreign countries, resulting in higher delays and poor performance for consumers.

In a nutshell, CDN refers to groups of servers that are distributed in various geographic locations and work together to provide fast delivery of Internet content. The

CDN takes content that is otherwise hosted on a single server and replicates it to a set of distributed servers that are deemed to be closer to the intended consumers of such content. On the other hand, content that is not supported by CDN infrastructure generally remains within its original server location. This means that, while locally hosted content will be closer to the local consumers, CDN-based content can be brought closer to consumers even if the original servers are in distant locations. The expectation, therefore, is that level of delays for CDN-based websites should be similar to locally hosted websites. Of course, this assumes that the CDNs have nodes within or close to the respective countries. In this regard, the South African case is worth a mention. Although the country has only about 46% of the news websites hosted locally, it can be seen the median RTTs for local and remote websites are almost the same; 22ms and 25ms, respectively. As was mentioned earlier, the leading remote hosting providers for Africa (Cloudflare, OVH SAS, Google LLC, GoDaddy.com and Unified Layer) operate on Cloud infrastructure and distribute their content via CDN services. It is also worth noting that South Africa hosts a number of CDN nodes, including Cloudflare, which has two; one in Cape Town and another node in Johannesburg[5]. This means that although the original web hosting is in remote countries, the actual website content is generally served from within the country. CDNs are helpful primarily to bring content hosted overseas closer to its users, and the increase in local traffic might become an incentive for local ISPs to peer locally.

With regards to local news websites, it is interesting to make some comparison between remote websites that are hosted by CDN-enabled networks (see Figure 5.3) and those hosted on other networks. It is observed that in 80% of cases, remote websites hosted on CDNs have a latency of 200ms as opposed to 275ms for websites hosted without CDNs. A clear benefit can be drawn from using CDNs, but of course this comes with a cost.

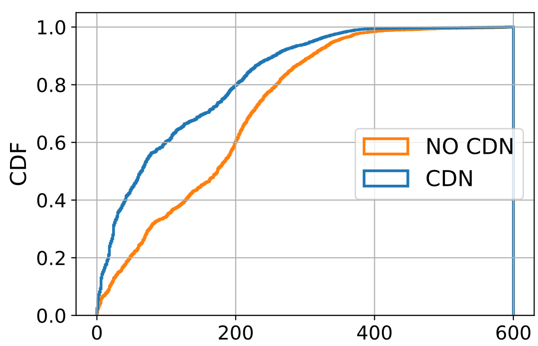


Figure 5.3: RTT for websites using CDN vs NO CDN

[5]https://www.cdnplanet.com/geo/south-africa-cdn/

5.1.4 Observation

The main observation for this case study is that 85% of the African local news websites are hosted outside of their respective countries, mostly Europe and US, while the majority of the websites that were observed to be hosted within Africa were based in South Africa. Almost all the countries in the sample have less than 30% of their websites hosted locally, and about half of all the countries have less than 10% local hosting. 68% of all the Internet path for accessing African websites from African countries traversed outside Africa, mostly through US and European networks. This network-level analysis showed that most of the local African news websites are hosted by foreign companies.

The leading providers for Africa's remotely hosted news websites are largely based on Cloud infrastructure and make use of content distribution networks to mirror the content locally. One direct consequence of remote hosting is that African network operators have to use significant levels of international bandwidth to fetch African content for their clients. The cost of this international bandwidth is at the end, passed on to the Internet users in Africa.

Furthermore, geolocation of website hosting has significant implication on performance. The median RTTs for locally hosted websites is generally lower than the RTTs for remotely hosted websites. However, in some countries, the median RTTs for locally hosted websites is higher than for websites that are remotely hosted. High RTTs levels for locally hosted websites is an indicator of circuitous paths, which are due to lack of local ISP peering. Rather, in these cases interconnections between local networks is done through networks in remote countries. In the absence of local peering, local hosting of websites tends to resolve into circuitous routes for accessing the content than when the websites are in foreign countries, resulting in higher delays and therefore in poor performance for Internet users. By bringing remotely hosted content closer to the users, CDN-enabled networks reduce delays for CDN-based websites. Although the level of delays for CDN-based websites is similar to locally hosted websites, CDNs do not improve the performance of locally hosted content in cases where there is lack of local peering. While access network infrastructure has improved in Africa, the content infrastructure has lagged behind. There is a considerable difference between access infrastructure and content infrastructure. While supply-side policy and regulatory interventions have positively affected access infrastructure (notably the roll-out of mobile networks in the case of Africa), content infrastructure has not always been enabled by national policy and regulatory interventions resulting in most of the content in Africa being hosted and accessed from overseas. This configuration is not ideal, as it increases latency levels and costs to access content. Not having a reliable hosting infrastructure also affects in-country delivery infrastructure. Without the necessary local peering, locally hosted content can exhibit equally higher access latencies.

5.2 Case study II: Public sector websites

The aim of this study is to quantify Internet latency as a barrier to the adoption of cloud computing services by Internet users in the public sector, namely by analysis public sector websites. This will highlight the quality of service for accessing content hosted in various networks and geographical locations, including cloud-based infrastructure. The rationale is that the success of cloud-based services for the public sector will depend on the ability to achieve high-performance connectivity to the cloud. This study, therefore, provides insight into the readiness of the public sector in the five selected countries to interact with cloud-based services. After characterising the network performance — the study will also explore the causality behind any observed sub-optimal performance (e.g. high delays), and the possible cloud-computing readiness steps that need to be undertaken. In particular, the study seeks to characterise the level of when accessing public sector's online public resources. Performance data was collected via Internet measurement campaigns targeting public sector websites sampled from five countries: Nigeria, Ghana, Kenya, Zambia and South Africa.

5.2.1 Research questions

The three key questions addressed in this case study are as follows:

1. In which networks and countries are the public sector websites currently being hosted. This question is meant to provide some insight on the current hosting practices in the public sector, particularly regarding the extent to which websites are hosted locally within a country, or remotely. This will also shed light on the locality of networks that are dominating the public sector hosting market in Africa.

2. What are the characteristics of country-specific Internet latencies to web servers of the public sector? This question is meant to provide country-specific delay characteristics and comparison for public sector websites hosted in various networks and countries.

3. What is the extent of circuitous routing when accessing locally hosted websites, and what impact does this circuitous routing have on the Internet delays?

5.2.2 Research methods and data sources

This section describes the process for conducting measurements to gauge the readiness of the public sector to utilise cloud-based resources. The first step involves identifying the appropriate set of performance metrics that can reveal the readiness of the public sector to utilise cloud-based services. This is followed by the process of selecting the appropriate tools and platform for conducting the measurements. After selecting the measurement platform, it is necessary to select the locations from which to observe performance (i.e. measurement vantage points), as well as appropriate measurement targets.

5.2.2.1 Selection of countries

It is most of the time extremely difficult to have vantage points in all African countries. In order to make this study representative of the African landscape, five countries were chosen namely Nigeria, Ghana, Kenya, Zambia and South Africa. South Africa was chosen as benchmark as one of the leading countries in terms of Internet ecosystem maturity. Nigeria, Ghana and Kenya are emerging countries with a strong Internet growth. Zambia was an interesting case to consider as it is a land-locked countries but it has a highly-developed terrestrial fibre ecosystem and good cross-border connectivity with neighbouring countries.

5.2.2.2 Performance Metrics

The public's high concern for "system performance", as reported in the study of Brenda Scholtz *et al.* [9] highlights the perceptions that Internet infrastructure in many African countries is not developed and robust enough to provide reliable and high performance access to computing resources and information stored in the cloud. One aspect of this relates to high end-to-end delays (latencies) that impact responsiveness and quality of experience (QoE) for online interactions. Latency is an important metric for cloud computing as it gives insight into responsiveness of interactions between cloud servers and Internet clients.

5.2.2.3 Measurement Platform and Vantage Points

A number of Internet measurement platforms have deployed thousands of probes in access and backbone networks, as well as behind residential gateways, globally. Researchers are able to make use of these platforms to conduct Internet measurement campaigns, using the specialised network devices (probes) as vantage points from which to launch tests towards specified targets. Recent measurement platforms use dedicated hardware-based probes, and these probes are used to run continuous measurements with minimal end-user participation. When selecting a distributed Internet measurement platform for a large scale campaign, it is important to consider the number and distribution of vantage points in networks that are to be measured [133]. Shavitt *et al.* (2011) showed that extensive topology sampling from a broad and distributed vantage points is required for obtaining unbiased and accurate topology characteristics. A more widely deployed hardware-based measurement platform is the *Ripe Atlas* [6], which consists of thousands of probes that perform active measurements. As of December 2017, RIPE Atlas had around 230 active probes in 36 African countries. On this basis, this study made use of Ripe Atlas for topology characterisation, measuring latency to public sector websites for five African countries. During each measurement episode, 10 Ripe Atlas probes were randomly selected as vantage points for each of the countries.

5.2.2.4 Measurement Targets

Public sector websites selection The next step in the study was to identify and select prominent websites from the public sector in each of the target countries. This was obtained through the AlexaTop[7], a website that ranks websites based on a combined measure of page views and unique site users. For each country, a filter was applied for 'Government' websites to list the prominent public sector websites, such as those for government departments and parastatal organisations. For example, '.../Top/Regional/Africa/Kenya/Government' would list the most popular government-related websites in Kenya. In some cases, expert local knowledge was sought to determine prominent public sector websites in each of the five countries. In total, 86 websites were identified as measurement targets across; 10 in Kenya, 9 in South Africa, 10 in Zambia, and 48 in Nigeria.

[6] https://atlas.ripe.net/

[7] AlexaTop Website, last accessed on 2021-04-28, https://www.alexa.com/topsites

Representativeness and limitations The number of websites selected for this case study, albeit small, gives a rough idea of the situation of content hosting in the selected countries. Other countries not studied here might have slightly different variations.

5.2.2.5 Launching Measurements

Traceroute measurements were then launched from each of the selected Atlas probes towards each of the country's selected public sector websites. The actual measurement was performed towards the IP address of the web server for each website. To obtain IP addresses, a DNS lookup was performed for each website domain. In order to mitigate the effects of location-based load balancing, where requests for a domain are directed to different web servers based on the location of Internet clients, the DNS lookups/resolution were performed from the vantage points (i.e. from each Atlas probe).

For each measurement episode, four traceroutes were launched successively from each Atlas probe to all of the country's selected websites, and this was repeated 4 random times a day for one month in December 2017. While not all Traceroute measurements could reach the final destination, a Traceroute measurement was considered successful it is was able to reach the hosting network, i.e. if the last hop in the Traceroute was inside the hosting company's network. In the end, a total of 13790 Traceroute measurements were successfully completed; 2570 in Ghana, 3073 in Kenya, 2790 in Nigeria, 3341 in South Africa, and 2016 Zambia.

5.2.3 Data analysis

This section describes the results of a measurement study on public sector websites carried out in the five selected countries. The results describe the remote locations and networks where the websites are hosted, the nature of routes for accessing the public sector websites in the respective countries, as well as the performance (delay) observed for each situation. The initial step in the data analysis involved attaching network and geolocation information to each target IP address (obtained from the websites' DNS lookups performed from the vantage point), as well as every router hop in the traceroute data. The RIPE Routing Information Service (RIS) and the MaxMind GeoLite2-City database [8] are used to obtain the Autonomous System Number (ASN) and the geographical location (country) of each IP address. While it is well known that

[8]https://www.maxmind.com/en/geoip2-city

geolocation databases do contain inaccuracies, the analysis in this study is restricted to country-level geolocation which has relatively much higher accuracy.

5.2.3.1 Geolocation of Web Hosting for the Public sector

One of the key goals of this study was to examine the ASN and geographical distribution of web hosting servers used by the public sector in Africa and to evaluate the performance implication of such a distribution. This should also reveal the strengths and weaknesses of the web hosting environment in the selected African countries. The first step in the analysis was, therefore, to compute the geographical and network distribution of public sector websites per country.

The first observation from the analysis was that, on overage, 66 per cent of the sampled public sector websites were hosted outside their respective countries, i.e. remote hosting. It was also noted that the level of remote hosting varies widely among the countries, ranging between 4 and 82 percentage. Figure 5.4 shows the percentages of remote and locally hosted public sector websites in each of the five countries. Of the five, South Africa had the lowest percentage of remote hosting at 4 per cent, whereas Nigeria and Ghana had the highest remote hosting of 61 and 82 per cent, respectively.

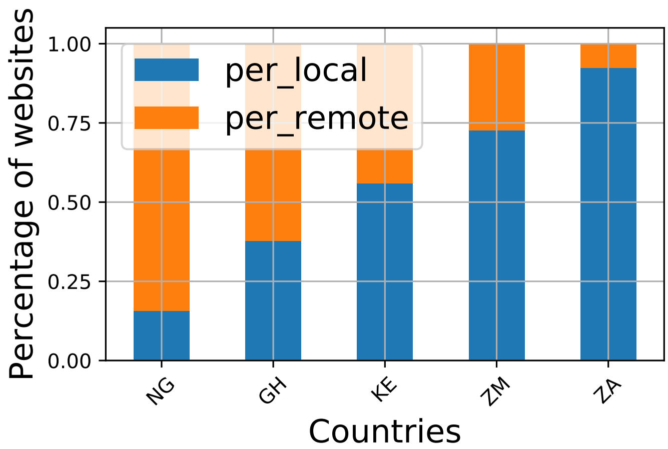
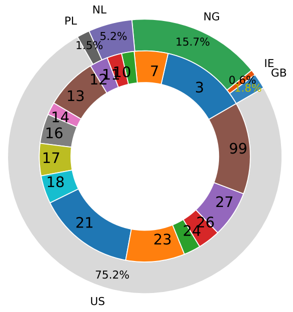


Figure 5.4: Percentage of local and remote hosting of public sector websites per country

From Figure 5.5, it can be seen that most of the remote website hosting is situated in USA, UK, Germany, Canada and Ireland. Figure 5.5a shows that Nigeria, for example, had 75% of the websites hosted in US-based companies, mostly through New Dream Network (14.8%), RackSpace (9%), GoDaddy (8%), and Unified Layer

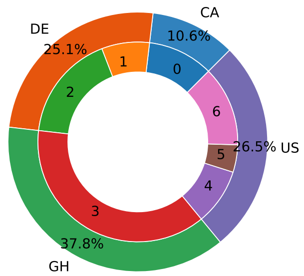
(7%). For Ghana, the remotely hosted websites are mostly in the US (26.5%), Germany (25%) and Canada 10%). Kenya and Zambia have a higher percentage of public sector websites locally hosted. Interestingly for both, local hosting of public sector websites appears to be supported by their respective National Research and Education Networks (NRENs); in Kenya, 37.9% of the websites were hosted in KENET (Figure 5.5c), whereas in Zambia, 25.3% of the websites were inside ZAMREN (Figure 5.5d).

Figure 5.5: Pie-charts showing hosting countries and networks most used by each vantage country



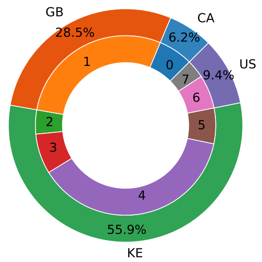
3 - NG/Galaxy Backbone PLC (13.1 %)
7 - NL/Microsoft Corporation (5.2 %)
13 - US/GoDaddy.com (8.0 %)
21 - US/New Dream Network (14.8 %)
23 - US/Rackspace Ltd. (9.0 %)
27 - US/Unified Layer (7.1 %)

(a) Nigeria



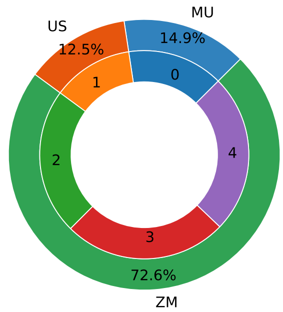
0 - CA/OVH SAS (10.6 %)
1 - DE/ 1&1 Internet SE (7.7 %)
2 - DE/Hetzner Online GmbH (17.3 %)
3 - GH/GGoC1-AS (37.8 %)
4 - US/Codero (9.1 %)
6 - US/Rockynet.com (13.0 %)

(b) Ghana



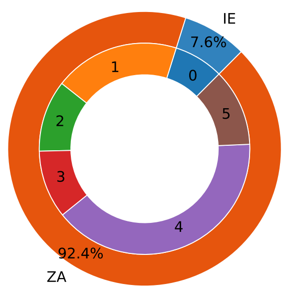
0 - CA/UptimeArchive (6.2 %)
1 - GB/KENYAWEB (28.5 %)
2 - KE/ACCESSKENYA (4.3 %)
3 - KE/JAMBONET (7.2 %)
4 - KE/KENET (37.9 %)
5 - KE/SIMBANET-AS (6.4 %)
6 - US/Cloudflare Inc (6.1 %)

(c) Kenya



0 - MU/Liquid Telecom Ltd (14.9 %)
1 - US/CyrusOne LLC (12.5 %)
2 - ZM/ZAMNET-AS (22.7 %)
3 - ZM/ZAMREN (25.3 %)
4 - ZM/ZAMTEL (24.7 %)

(d) Zambia



0 - IE/Amazon.com (7.6 %)
1 - ZA/IS (19.3 %)
2 - ZA/Neotel Pty Ltd (11.0 %)
3 - ZA/SITA-AS (10.4 %)
4 - ZA/Telkom-Internet (39.9 %)
5 - ZA/Vodacom-VB (11.8 %)

(e) South Africa

South Africa had only one of the sampled websites hosted outside the country, in Ireland (Figure 5.5e). The remote website was hosted in the Amazon cloud infrastructure, using their data centre in Ireland. The result for South Africa was as expected, particularly considering its significantly more developed web-hosting infrastructure compared to other African countries. It also needs to be noted that the much robust Internet infrastructure in South Africa has also attracted many more foreign and cloud-based hosting companies, the result of which is that, while these companies appear to have a presence in the country, some of the content hosted by such networks is physically located in remote data centres. For example, while Amazon Web Services (AWS) has become popular in the South African market, the company does not operate a data centre within the country, meaning content hosted within the AWS infrastructure is remotely hosted.

5.2.3.2 Latency to public sector websites

It is important to highlight that choice of hosting provider, and where it is located, can have significant consequences on the level of delay experienced by Internet clients. The websites hosted in more remote places generally experience higher delays. While many of the dominant hosting providers make use of cloud-based infrastructure and, therefore, claim to have global presence, the absence of data centres and CDN (Content Delivery Networks) nodes in most of the African countries means that hosting in such networks would result in high overall delays. Many of the local hosting networks can be seen to have delays that are less than 100ms, whereas the higher delays are mostly for websites hosted by the large international operators. The high delays are particularly prevalent in situations where the remote hosting is not supported by CDN infrastructure that would otherwise push the content closer to where the intended audience is, i.e. closer to the countries owning the websites.

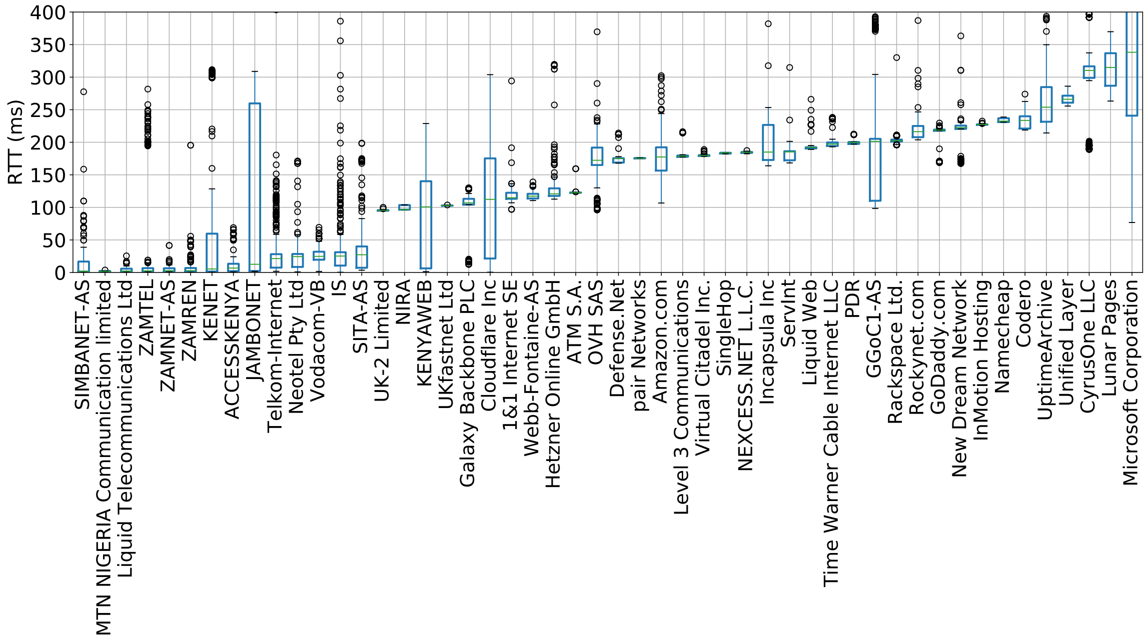
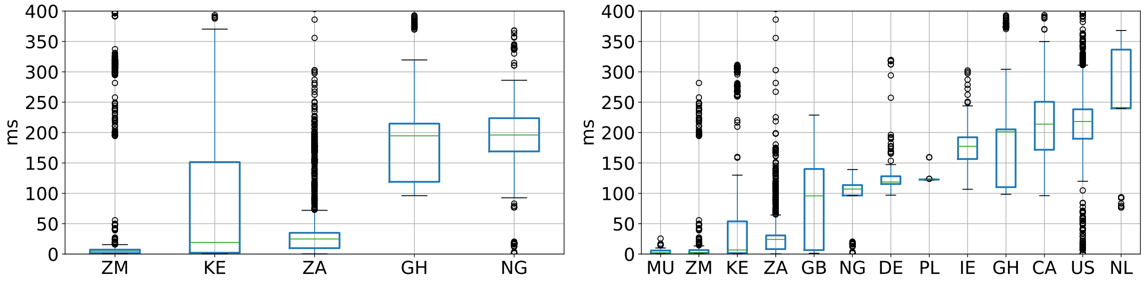


Figure 5.6: Distribution of round-trip-times for websites hosted in different networks

Figure 5.6 shows that hosting companies with average delays of over 200ms are mostly based in the US, including *Microsoft Corporation, LunarPages, RackSpace, GoDaddy,* and *New Dream Network*. On the other hand, *CloudFlare*, which is also US-based, runs a number of caches in Africa, including in South Africa and Kenya, and this is reflected in the lower median delay of 110ms when their content is accessed by Internet clients in Africa.

Figure 5.7a below presents a summary of RTTs to the sampled public sector websites as measured from each of the five countries. As is observed in Figure 5.7a, Ghana and Nigeria, the two countries with the highest remote hosting percentages in the sample, also had the highest median RTTs of 199ms and 177ms, respectively. In contrast, Kenya, which had an almost 50-50 split between local and remote hosting, had a lower mean RTT of 50ms. The best lowest mean RTT of 3ms was observed in Zambia, which also had much lower remote hosting of 25%.



(a) (b)

Figure 5.7: Figure 5.7a showing distribution of delays to per vantage country; and Figure 5.7b showing distribution of delays per hosting country

5.2.3.3 Impact of Hosting Locations

It is worth analysing the extent to which different host hosting countries result in different levels of delay for the selected African countries. Figure 5.7b shows the delays to websites hosted in different countries, and illustrates how websites hosted remotely, such as in USA, Canada and Netherlands experience significantly higher delays. As would be expected, the lowest delays were coming from the vantage countries. The only exception was Ghana, whose special case circuitous routing discussed later. In general, the further away a website's hosting country is, the higher the delays. It can be observed that the highest delays are for websites hosted in Canada and the USA (median RTT of 230ms and 220ms, respectively), the two countries are geographically the furthest of the hosting countries from any of the five vantage countries in this study. The cumulative distribution in the left plot of Figure 5.8 shows that about 50% of the delay samples in Ghana and Nigeria were above 200ms. In comparison, only 20% in Kenya, 19% in Zambia, and less than 1% of samples in South Africa were above 200ms. About 10% of the samples in all countries, except South Africa were above 300ms. In terms of hosting countries, the right CDF in Figure 5.8 shows that the higher delays are more prevalent for websites hosted in USA, Canada, and Netherlands. About 50% of the delay samples to these countries are above 250ms.

Different countries experience different delays to websites hosted in the remote locations. Figure 5.9 presents delays from the vantage countries to websites hosting countries. The differences can be attributed to the differences in geographical distances, as well as varying logical topologies. Among the countries hosting in the USA, it can be seen that Zambia experiences the highest median delay of 314ms. This should be expected given Zambia's geographical distance from the USA, compared to Ghana, Nigerian and Kenya, which experience median delays to the USA of 221ms,

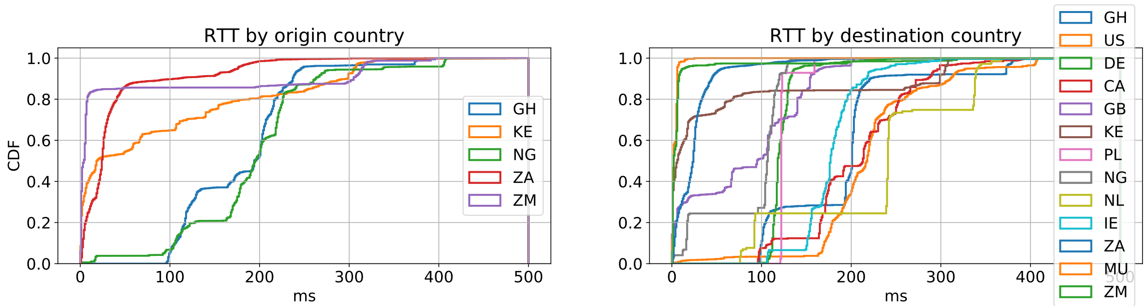


Figure 5.8: Cumulative distribution of latency values for each vantage country (left), as well as for each hosting country (right)

200ms, and 174ms respectively. In the case of South Africa, the only remote hosted website was in the Republic of Ireland, where *AWS* has a data centre. In terms of performance, the median delay between South Africa and the Republic of Ireland is observed to be 180ms.

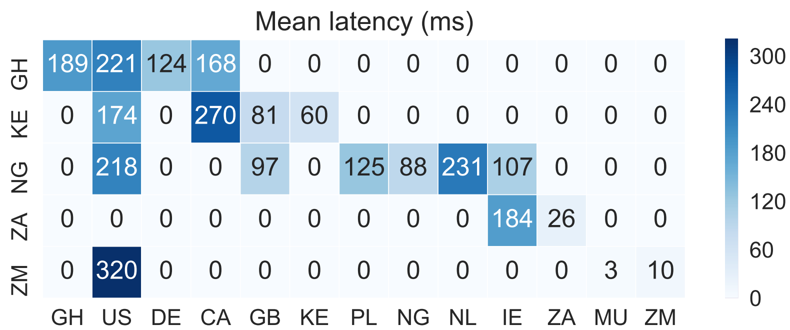


Figure 5.9: Matrix of mean latencies from the vantage countries (x-axis) to website hosting countries (y-axis)

5.2.3.4 Impact of Circuitous Routing

It is generally the case that local hosting provides lower delay compared to remote hosting, and the dataset from Zambia and Kenya exhibit this expectation, with local delays of 2ms and 9ms, respectively. Ghana and Nigeria, on the other hand, go against this trend. In the case of Ghana, there was a median delay for locally hosted websites of 201ms, while the country's websites hosted in Great Britain had a lower median delay 118ms. Similarly, while the local median delay for Nigeria was observed to be 107ms, a slightly lower median delay of 97ms was observed for websites hosted in Great Britain.

To evaluate this phenomenon, another aspect of this study was to look at the extent and impact of circuitous routing when accessing public sector websites. In this context, circuitous routing is when a website that is locally hosted is accessed by local Internet clients through paths that traverse other countries. Overall, 23% of the websites were accessed circuitously, but this is more prevalent some countries than others. For example, the Ghana dataset had the highest percentage of circuitous routes at about 33%, while Kenya was at 16% and Nigeria at 11%. Figure 5.10 shows a distribution of RTTs for the three categories of routes. The general distribution does show that locally hosted websites that are accessed through circuitous routes, ie routes that leave and come back to the vantage country, experience higher delays than websites that are remotely hosted.

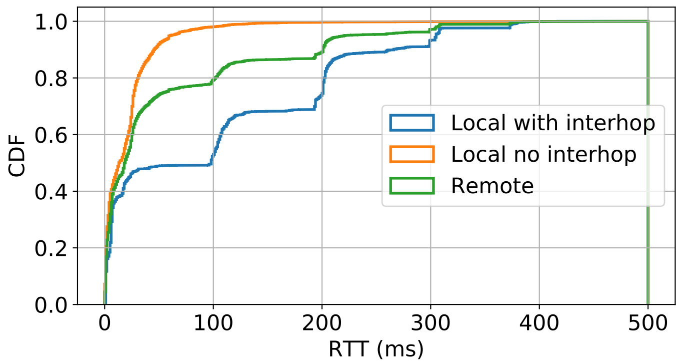


Figure 5.10: Cumulative distribution of latencies, indicating differences between local and remote hosted websites, and also for local websites that are accessed via circuitous routes

Circuitous access of locally hosted websites, and the result high latencies are symptomatic of lack local peering of networks within a country. With locally hosted websites appearing to perform worse than remotely hosted websites, the lack of peering has the potential to not only discourage local hosting, but also inhibit success local content initiatives.

5.3 Conclusion

This chapter has provided empirical evidence on the current configuration of web content hosting, access, and distribution in Africa, and has demonstrated that the status of the African content infrastructure is alarming. Both of the above case studies have shown very similar results in terms of latency to access content that are hosted remotely. This tends to suggest that the two proxies selected to represent *local content* are actually very similar (and relevant).

Most of the African countries heavily rely on foreign services, both to host, to access, and to distribute local content in Africa. Latency levels to remotely hosted local content are high as well as costs of accessing remotely hosted local content. It has also shown that in some African countries, access to public sector websites is largely characterised by high Internet delays. In addition, a large proportion of public sector websites are currently being hosted remotely, i.e. in other countries. It was also observed that of the five countries surveyed, Nigeria and Ghana had the highest percentage of remote hosting and experienced the highest latencies. A large portion of the remote websites were hosted in USA, Canada, Germany, UK, and South Africa. While the hosting networks generally have global operations, they do not necessarily have physical infrastructure in most of the African countries. This means that while offering the convenience of cloud-based hosting, lack of physical infrastructure in Africa entails that Africa's web content gets to be stored in remote locations. Remote storage of web content has a negative implication on the sovereignty of African countries in that they lose control of their data, especially for government-run Internet services.

In addition, the burden of fetching content from remote locations falls on local network operators, the cost of which gets passed on the users. This ultimately has negative implications on the local economies, and also in terms of poor quality of experience due to high latencies as reported in this study.

To reduce these latencies and to help improve performance of cloud-services in Africa, there is need for leading cloud infrastructure providers to deploy infrastructure in Africa. The advantage of local deployments was demonstrated in the results from Kenya, which although had a relatively high percentage of remote hosting (42%), appeared to have a much lower median web delay of 50ms. In comparison, Nigeria and Ghana had mean latencies of almost 200ms. However, for African countries to fully take advantage of cloud infrastructure that is domiciled on the continent, there is need for better peering and interconnectivity at national and continental level.

Finally, most of the public policy strategies on improving local content in Africa focused on demand-side interventions, such as the creation of content in local languages, and on developing skills on web content production and consumption. While these policies are important, bodies in charge of the governance of the Internet are urged to identify ways of facilitating local markets for content hosting, access and distributions by focusing on: (1) incentivising investments on data centres and web farms in Africa, to stimulate economies of scale for the local web hosting market; (2) encouraging local news websites to move the content closer to the users in Africa, by incentivising the use of CDN-enabled networks and by reducing prices for local hosting, (3) facilitating peering relationships between ISPs and investing in local exchange points to reduce latency; and (4) incentivising ISPs to peer in local exchange points.

Chapter 6

Evaluating Alternative Content Delivery Mechanisms

In the previous chapter, this thesis elaborated on the barriers to provide good Quality of Service (QoS) to end-users with regards to local content delivery. Several initiatives, including Facebook's Free Basics and Google Accelerated Mobile Pages (AMP), are currently being rolled out in a few countries around the world. Whilst their goals are similar, i.e. to deliver content to end-users with the least overhead in terms of cost and performance, their respective content delivery models are intrinsically different. Free Basics adopts a "cost-based" approach by zero-rating its services, while AMP chose a "performance-based" approach to deliver content. This chapter provides an in-depth analysis of both platforms.

6.1 Content delivery using zero-rated services: an analysis of the Free Basics program

Internet.org [134] is a consortium founded and led by Facebook since 2013 with the goal of bringing affordable Internet access to everyone in the world. Free Basics is the flagship initiative by Internet.org, offering *free* access to select Web services in partnership with mobile (cellular) service providers in developing and under-developed countries around the world. As of May 12^{th} 2016, Free Basics has been deployed in over 40 countries in Africa, Asia, and Central and South America, with a total population of over 1.26 billion (22% of the world population) [135].[1] Compared to developed countries, these countries have low Internet penetration rates (on average less than 20.4% of their population access the Internet) [136]. However, mobile phone

[1] Free Basics' deployment is also rapidly expanding with eight countries, including Nigeria with 180 million people, added to the list between May 1^{st} and Aug 15^{th} 2016.

usage rates in these countries are very high (on average about 101.7%[2] [137]), making mobile phone users a ripe target for expanding Internet usage. Free Basics, if successfully deployed worldwide, has the potential to bridge the digital divide [138].

This study of Free Basics is motivated by the following high-level question: *Free Basics is free, but at what quality?* Today, beyond the limited information provided by Free Basics themselves, there is little measurement data on the quality of Free Basics services or how the service quality is affected by Free Basics' design. As shown in this work, gathering data on Free Basics is challenging as existing measurement infrastructures that use the traditional Internet (e.g. PlanetLab [139] and Measurement-Lab [140]) cannot reach into or be reached from the walled Internet of Free Basics services and users. However, data-driven studies of Free Basics are necessary to help inform the public debates about Free Basics, which in early 2016, have led to Indian telecommunication regulators blocking Free Basics to over a billion potential users [141, 142].

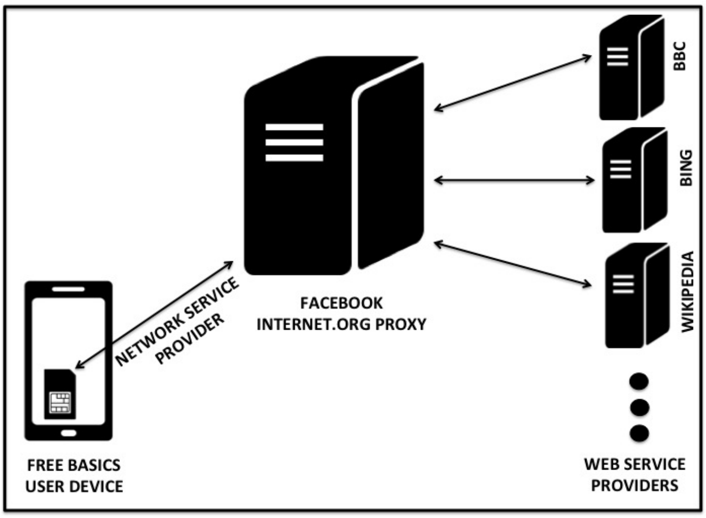


Figure 6.1: Free Basics architecture

How Free Basics works Before outlining the research questions motivating this study, it is useful to understand the service architecture of Free Basics. As shown in Figure 6.1, the Free Basics service comprises three independent service providers: (i) *network service provider:* the cellular carriers that agree to carry data for any Free Basics service at no cost to the end user, (ii) *Free Basics proxy service provider:* all Free Basics traffic is routed via proxies that are currently run by Facebook, and (iii) *web service providers:* to have their services accessed by Free Basics users, web

[2] >100% because people can have multiple subscriptions

site operators are required to first redesign their services following a set of technical requirements [143] and next apply to have their service approved by the proxy service provider [144]. The Free Basics platform is open to include any web service that meets the stated technical requirements (e.g. absence of JavaScript, high resolution images, videos or iFrames).[3] Such restrictions are put in place to support the target population of mobile users in developing regions, where mobile devices may not have full Web browsers and must access the Internet via WAP or similar technologies [145].

Any mobile subscriber of the participating network service providers can access (free of charge) the list of approved web services by going to `freebasics.com` using their mobile browser or by installing the Free Basics mobile application [146] (while connected to their cellular provider's network).

The architecture of Free Basics, while simple, has sparked acrimonious public debates. One key issue is the gate-keeper role played by Facebook, since the proxy service provider is not only determining which web services are accessible and what technical specifications they should meet, but also has access to all (mostly unencrypted) end user traffic.[4] A second key issue is the (price) differential treatment of data traffic related to Free Basics services by network service providers [142].

The goal: Assess the QoS of Free Basics In this chapter, the main focus is on understanding the impact of Free Basics architecture on the QoS offered by Free Basics in practice. Specifically, this study assessed the QoS offered by the three service providers comprising Free Basics:

1. *Proxy service:* It characterised the selection of web services accessible via proxy on Free Basics.

2. *Web services:* It compared the functionalities of web services tailored for Free Basics to their unmodified versions on the Internet.

3. *Network service:* It analysed the network performance (measured as bandwidth, latency, and page download times) for Free Basics traffic compared to that for paid traffic to the same site on the same carrier.

The study performed the above analyses using data from a preliminary study of Free Basics deployments in two countries, namely Pakistan[5] and South Africa.

[3] This was validated using a custom web service submission.

[4] Note that Facebook states that they only inspect domain names and traffic volumes, and that they (curiously) store any cookies "in an encrypted and *unreadable* format."

[5] In this study, Pakistan was chosen as a developing country where Free Basics was available. Pakistan is comparable to Nigeria in terms of GDP per capita, population size and mobile subscription rate.

The data for this study was gathered between April and August 2016. At a high-level, the measurements show that while several tens of web services are accessible on Free Basics, their functionality is somewhat restricted and the network performance for Free Basics traffic is poor (compared to paid network access). This research highlighted opportunities for a more informed public debate with the findings.

The public debate around Free Basics: The arguments both `for` and `against` Free Basics architecture (shown in Figure 8.6) are compelling: The `for` camp led by Facebook argues that Free Basics services are analogous to Public Libraries, offering free access to a limited selection of books. According to this camp, (a) Free Basics targets user populations that have never been online, (b) many (50% of) first time Free Basics users convert to paid Internet users within the first month [147], which incentivises network service providers to offer their service for free, (c) the technical specifications for web services are necessary to make them easily accessible to Free Basics users, many of whom use resource-constrained and cheaper feature phones, and (d) the proxy service not only provides an easy way for network service providers to differentiate paid and free traffic, but it also helps ensure that web service providers are adhering to technical specifications.

6.1.1 Measurement Methodology

To assess the QoS of the three service providers comprising Free Basics, data needs to be gathered (a) the set of Free Basics web services, (b) the webpages of these services to analyse the functionality they offer and the network performance while downloading them, and (c) the webpages of the same web services on the normal Internet, to compare the QoS of a Free Basics service with the QoS of the normal version (using paid access).[6]

To collect the above data, there was a need to access Free Basics service providers. However, it was found that access to Free Basics (including its proxies and web services) was restricted to mobile devices registered with a cellular service provider (i.e. with a SIM) in a country where it was offered. These restrictions make measuring Free Basics challenging as no network measurements from a machine outside of a Free Basics provider can reach a Free Basics proxy or the sites it serves. Measuring Free Basics required, at a minimum, a physical mobile device connected to an appropriate Free Basics network provider in the country where it was deployed.

[6]The term *normal* refers to sites outside of the Free Basics ecosystem.

Figure 6.2: Experimental setup

Experimental setup To measure Free Basics, experimental testbeds in the Lahore University of Management Sciences in Pakistan and the University of Cape Town in South Africa were created. Collaborators from each of these two locations set up a smartphone with the necessary SIM connection. This smartphone acted as a Wi-Fi hotspot with a desktop tethered to it. A remote connection was established to the desktop to measure Free Basics via crawler scripts (with browser user-agent spoofed to an appropriate mobile web browser) and network monitoring tools. The setup is shown in Figure 6.2.

Data gathered Using the above testbed, the following data were collected: (a) the list of all web services accessible via Free Basics in both Pakistan and South Africa; (b) the homepages of all web services available in Pakistan and some additional pages for a subset of services for network performance analysis (described in more detail in Section 6.1.4.1), and (c) the pages for the normal Internet versions of the same services, over the same cellular provider but with paid network connection (where downloads count against a data plan unlike Free Basics content). The URLs for downloading the normal Internet versions of the web services from their corresponding Free Basics URLs were extracted in an automated way.[7]

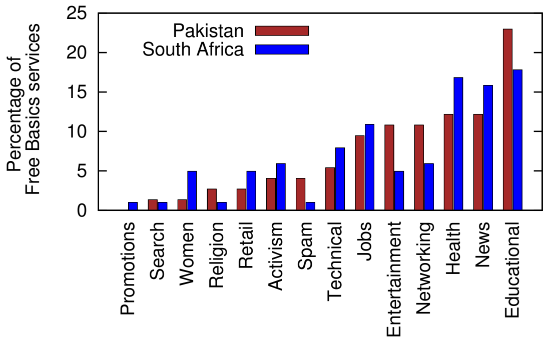
6.1.2 Assessing QoS of Free Basics

In this section, the study characterised the selection of Free Basics web services and compared the functionality and network access quality of these web services to their normal Internet counterparts (using paid access).

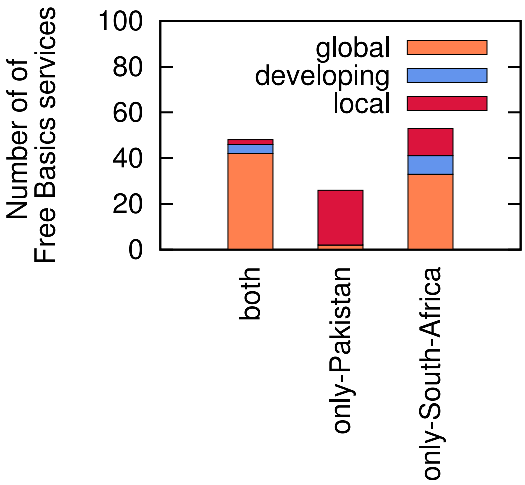
[7]Currently, Free Basics URLs use a common format, "https://http[s]-[subdomains-separated-by-dashes]-[domain]-[tld].0.freebasics.com/[URI]?iorg_service_id_internal=[...]", where the corresponding URL is "http[s]://subdomain.domain.tld/URI". For example, the Free Basics URL https://http-example-com.0.freebasics.com/test/?... can be converted to the non zero-rated version http://example.com/test.

6.1.3 Selection of accessible web services

The study explored the web services accessible via Free Basics deployments in Pakistan and South Africa. As of May 2016, there were 74 services in Pakistan and 101 in South Africa. The service listing in each country came with a brief description of what each service does. These descriptions were used to manually categorise the services according to their functionality, as shown in Figure 6.3(a). There was a significant fraction of services in the education, news, health, networking, entertainment and jobs categories.



(a) Service categories



(b) Service relevance

Figure 6.3: Categories of Free Basics services in Pakistan and South Africa

Furthermore, the study categorised the services according to whether they were relevant to a global audience, country-specific audience (local), or to an audience in a developing region (Table 6.1). Figure 6.3(b) shows the proportion of services in each relevance category. It also split the services based on whether they were available in both countries, or only in one specific country. The figure shows that a significant fraction of globally relevant services are available in both countries, and that Pakistan's Free Basics menu had a higher proportion of locally relevant services compared to South Africa.

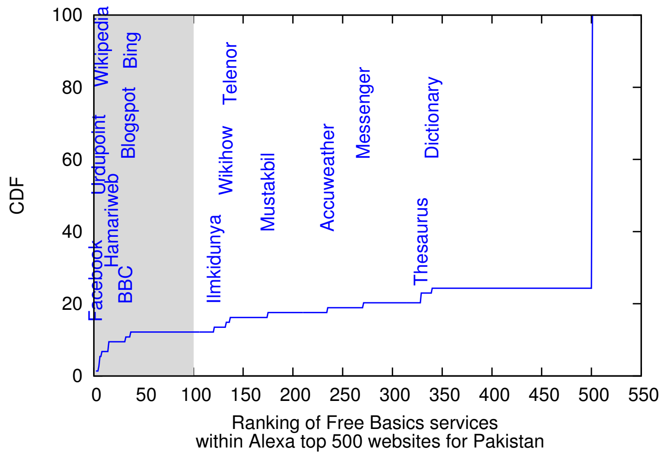
Relevant context	Characteristics
global	news, education, technical know-how, search etc., that are useful to anyone in the world
developing	information on manual farming, sanitation education, e.g. protection against mosquitoes and viruses (Malaria, Zika, Ebola, HIV)
local	news, entertainment, retail information, etc., that are locally relevant, mostly with native language support

Table 6.1: Categorisation criteria for Free Basics services based on relevance

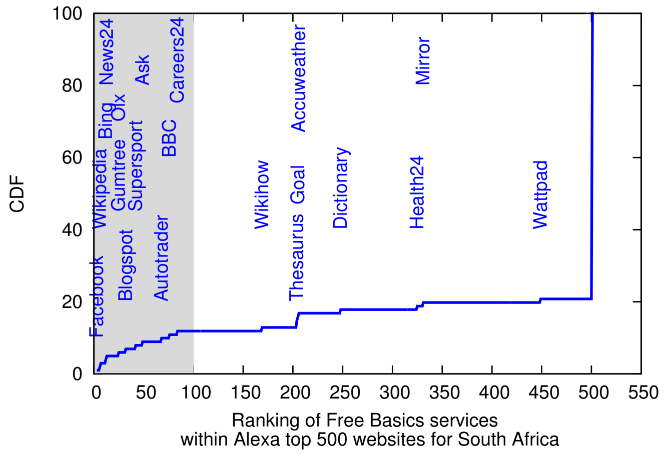
Figure 6.4(a) and (b) characterise the popularity of the Free Basics services, based on the Alexa website rankings *for that country*. Figure 6.4(c) characterises the services based on their *global* popularity. The figures show that very popular content globally (presumably the "basics" in Free Basics) was often included in Free Basics, including Facebook, Wikipedia, Bing and BBC. However, these popular sites accounted for a small fraction (≈20%) of the available services, while other services included in Free Basics fell below the top 2000 globally popular services, or top 500 nationally popular services, as ranked by Alexa. Another interesting thing to see was how the service list grew over time.

A key takeaway was that many globally/nationally popular services did not participate in Free Basics, but a wide variety of sites across multiple categories did. An important question is whether services with these characteristics (small number of globally and nationally popular services) are considered useful to Free Basics users.

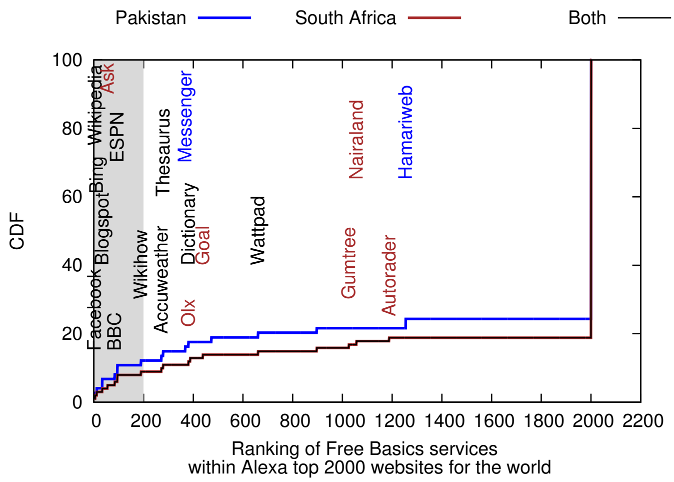
Interestingly, it was found that about 5% of the combined services in Pakistan and South Africa, were somewhat dubious. These were listed as "spam" in Figure 6.3(a)). Table 6.2 lists these websites and the reason why they were considered dubious. Some of these services were not available, returning an HTTP 404 error. Others generated "ISP warnings" that accessing the service will incur data charges, even though they should be accessible at no charge as part of Free Basics. Finally, there was the case



(a) Services in Alexa top 500 (Pakistan)



(b) Services in Alexa top 500 (South Africa)



(c) Services in Alexa top 2000 (Global)

Figure 6.4: Popularity of Free Basics services in Pakistan and South Africa

of an unremarkable individual's personal Facebook page,[8] included as a Free Basics service.

Service	Description
002CoSMos, news-byte.org, roktim.net16.net, tech-hints.in	HTTP 404 error on homepage
VOA news, bolloywoodking.in, mujahid islam	Data warning on homepage
www.facebook.com/***	Personal Facebook page

Table 6.2: Dubious Free Basics services in Pakistan

These examples suggested that the consortium that decides the list of services to be part of Free Basics might not necessarily be checking the services beyond ensuring that they meet the technical requirements. While additionally controlling content for quality may seem reasonable at face value, an important concern is how to do so without the perception (or realisation) of censorship. This is definitely an important issue needing careful attention as Free Basics grows. To be fair, this consortium, led by Facebook, does not state any quality control agenda at the submission portal. It claimed to check the submissions only for adherence to the technical specifications. Thus presence of these dubious services might be a confirmation of the consortium not exerting any censorship, just like the normal Internet not censoring spam websites. This trade-off between *absence of censorship vs. presence of some specious services*, is open for debate.

6.1.4 Functionality of accessible web services

To understand the impact of Free Basics' technical requirements for participation on service quality, the study compared the Free Basics versions of services with their normal Internet counterparts. Specifically, the homepages of all Free Basics services in Pakistan were downloaded, for both the Free Basics and the normal Internet version.

These sites were tested using URLs that correspond to the same content available both in the paid and the free versions of the web services, thus enabling an apples-to-apples comparison, for the duration of the experiment, which made a head-on comparison feasible.

[8]The username is elided for privacy reasons.

The structure of these corresponding URLs is described in Section 6.1.1. A concern was that the content for Free Basics and paid versions of the site may differ due to caching at the Free Basics proxy. The study found no evidence of caching; rather, the main content was identical (except for changes such as elimination of JavaScript). Thus whatever updates are available in the paid version, were simultaneously available in the free version too. Content freshness did not seem to be affected by the presence of the Free Basics proxy.

Effect of technical specifications: Figure 6.5 shows a Cumulative Distribution Function (CDF) of the ratio of the sizes of these homepages, normal compared to Free Basics. It can be observed that 80% of the services have at least bigger sizes and potentially richer content for the paid version, compared to the Free Basics version. E.g. `MashAllah ElecTronics` and `Pharmaceutical Guidelines` are 15x-18x larger in the normal versions. This difference can be attributed to high-resolution images and multiple JavaScript files in the paid version, while only small images and no JavaScript are present in their Free Basics counterparts.

Next, the study measured the impact of Free Basics on the number and size of content accessed via links from the homepage (level 1 pages). Figure 6.6 shows the CDF of actual page sizes for all level 1 HTML objects for three selected services - BBC, Cricinfo and Mustakbil (a local job portal in Pakistan). It can be observed that page-size differences were service-specific, and BBC had much higher difference between its normal and free versions, while the other two had comparable sizes between versions. Similarly, certain services like BBC and Mustakbil had considerably fewer level 1 HTML objects in their free versions than their normal versions.

Further inspection of the services' homepages revealed the absence of any contextual and embedded advertisements in the Free Basics version of the services. The lack of advertisements was possibly due to the restriction on using JavaScript, which was commonly used to fetch and display ads. This restriction raised the interesting question of economic incentives of the web service providers, who might find it difficult to monetise their services in Free Basics.

The technical specifications were put in place to support the target population of mobile users in developing regions, where mobile devices may not have full Web browsers and must access the Internet via WAP or similar technologies [145]. However, the functional restrictions on Free Basics services and their implications for the number of sites participating (and the content they provide) required further investigation and discussion. For example, determining whether the users liked the offered services, despite functional restrictions, will require field studies with Free Basics users.

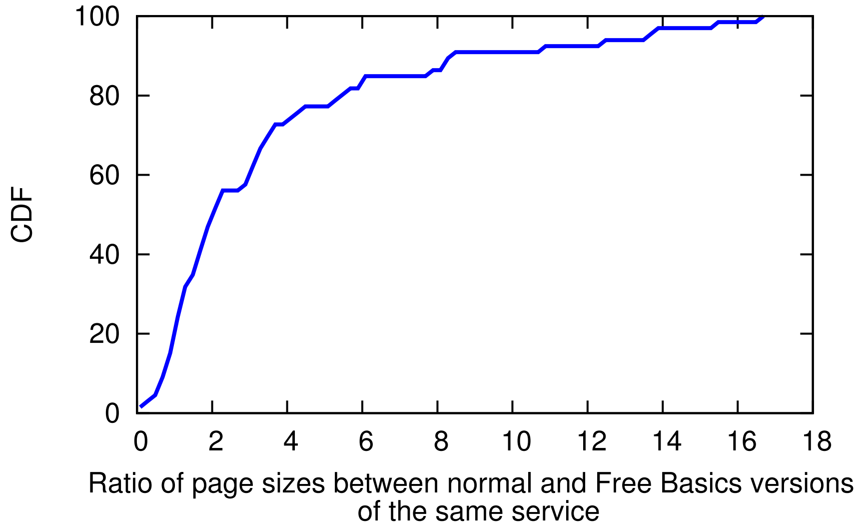


Figure 6.5: Ratio of homepage sizes

Effect of walled garden: Free Basics offered a limited set of services; accessing any Internet destination beyond that set was not blocked but would have incurred charges, with appropriate warnings shown to the user. To understand the impact of this "walled garden" on the user, the study approximated the size of the "garden" by visiting every link from the homepage of every Free Basics service to determine whether the result was a warning page indicating that the visited link is outside of Free Basics.

Figure 6.6 plots the CDF of the percentage of URLs linked in the homepage of the Free Basics services in Pakistan that were outside the Free Basics domain and give data warnings. There were some services like Accuweather, BBC and ESPN on the left, which were mostly self-contained. However, 60% of the services have external links, which will cause breaks in the user browsing experience. In some cases, such as `VirtualpediatricHospital.org`, `SumirBD.mobi`, 80-90% of the listed URLs are external links—somehow defeating the purposes of Free Basics.

An interesting example of this came from the Bing search engine, which was part of Free Basics in both South Africa and Pakistan. Table 6.3 shows the result for five representative searches in Pakistan, the number of results returned for each search, and number of those results that were accessible using Free Basics. The key take-away

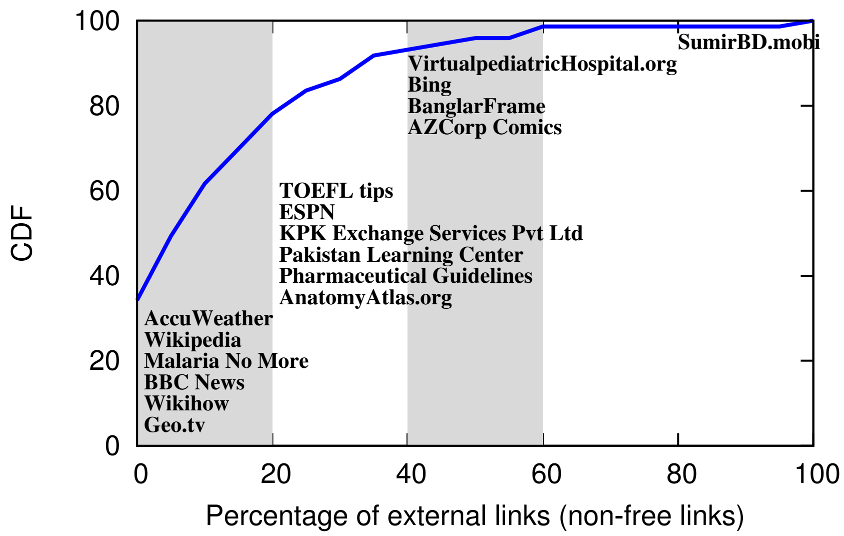


Figure 6.6: External links at home page of Free Basics services

was that the vast majority of Bing search results cannot be followed by Free Basics users without incurring data charges. When users input the search query in the first column in the Bing service for Free Basics, the second column showed the number of search results in the first page, and the third column showed how many of those results are also accessible through Free Basics. The other search results were external links, for which the user would be charged.

Search query	#results in first page	#Free Basics results in first page
Top universities in Pakistan	10	2 (both Wikipedia)
Pakistan news	13	0
Cricket	13	2 (1 Cricinfo, 1 Wikipedia)
Dengue prevention	10	1 (Wikipedia)
Jobs in Pakistan	10	0

Table 6.3: Functional breaks with limited number of Free Basics services returned by traditional search engines

Interestingly, it was found that it should be relatively easy to modify search output to rank the results based on their accessibility within Free Basics. This would have improved the user experience for all the queries in Table 6.3, as Free Basics had significant number of services related to education, news, health and job portals. This trade-off between *offering a good user experience while keeping users restricted within the walled garden vs. offering some tantalising content out of reach of the free* *program to give users a glimpse of the potential of the broader Internet*, is open for debate. Again, determining the merits of these approaches would require field studies.

6.1.4.1 Network performance

To measure the network service quality of Free Basics services, three representative services in Pakistan - BBC, Cricinfo and Mustakbil (a Pakistani job portal) were considered and the following experiment was carried out. The script downloaded the landing page of each service and also all pages linked to this first page. It started this download simultaneously for the Free Basics version of the service, and the normal mobile version with the paid connection. The script then logged the download time and the size for each page, which were used for a head-to-head comparison between these Free Basics services and their paid counterparts. The same experiment was repeated for BBC Free Basics and BBC paid versions in South Africa.

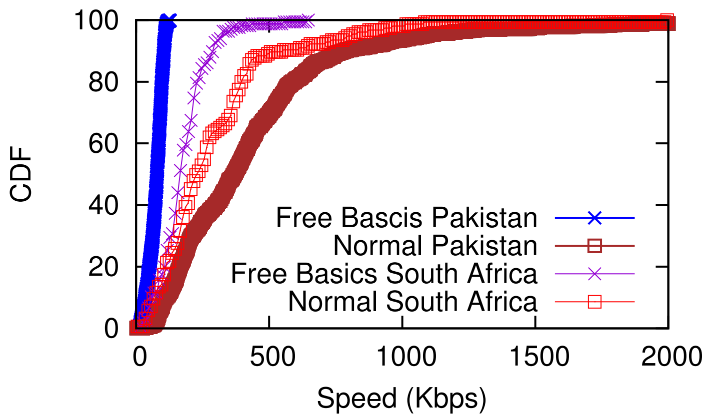


Figure 6.7: CDF of page fetch speeds

Page fetch speeds Figure 6.7 shows the CDF of network speeds observed for the two versions of the same services. The CDF is computed over 346 HTML pages of the Free Basics version and 560 HTMLs of the normal version in Pakistan and 155 HTML pages of Free Basics version and 166 HTMLs of normal version in South Africa.

A marked difference can be observed in the two speed distributions in Pakistan, the median speed being four times slower for Free Basics (80 Kbps), compared to the paid version of the same service (320 Kbps). The curve for the paid services shows a wide range of speeds typical of cellular broadband access, and indicating that the provider has a capacity greater than 1 Mbps. However, Free Basics downloads never experienced more than 128 Kbps, strongly suggesting that Free Basics traffic is throttled to a fraction of capacity.

The difference between the paid and free versions of BBC in South Africa was less than that in Pakistan. Still, in South Africa too, the free version never exceeded 600 Kbps, while the paid version saw more than double those peak speeds. In both Pakistan and South Africa, it was difficult to attribute performance differences to carrier-imposed throttling, proxy-imposed throttling, or path inflation on the path that includes the proxy.

Page Load times Figure 6.8 shows the effect of download speeds on user experience, the metric being page fetch times. For the four services, there is a median increase of 2 to 6 seconds in the page fetch times. The difference in page fetch times was also service dependent, Cricinfo seeing the worst delay followed by BBC and Mustakbil. This ordering followed the page size distribution of the services, where Free Basics version of Cricinfo had the largest pages, followed by BBC and Mustakbil. Thus services with richer content contributed to a substantially worse user experience.

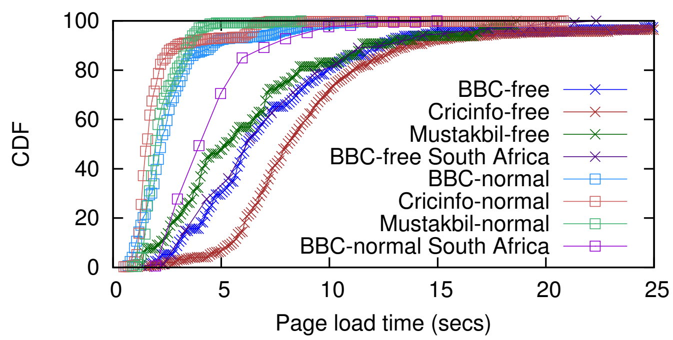


Figure 6.8: CDF of page fetch times by service

No evidence of whether different services within the same country saw differential service was found (i.e. Free Basics performance was neutral with respect to service). Specifically, performance between downloads of similar-sized pages from different services (not shown) were compared, and no performance differences were observed across the services.

Effect of proxy Xu *et al.* [148] found that the relative network locations of proxies between clients and servers can significantly impact performance. The study performed ping measurements to the IP addresses contacted for freebasics.com traffic to understand their network distance from clients. Interestingly, the reverse Domain Name System (DNS) name for these IPs was a hostname ending with facebook.com or fb.com (which verified the proxy-based architecture in Figure 6.1 as documented by Facebook). The script issued traceroutes and use city codes in reverse DNS records

Country	Pakistan	South Africa
freebasics.com average ping delay (ms)	326.8	714.12
direct website average ping delay (ms)	bbc.com - 297.15 cricinfo.com - 76.515 mustakbil - 346.25	bbc.com - 460.5
freebasics.com mininum ping delay (ms)	299	494
direct website minimum ping delay (ms)	bbc.com - 189 cricinfo.com - 54.4 mustakbil - 315	255

Table 6.4: Difference in ping delays between the Free Basics proxy and direct access to the web services

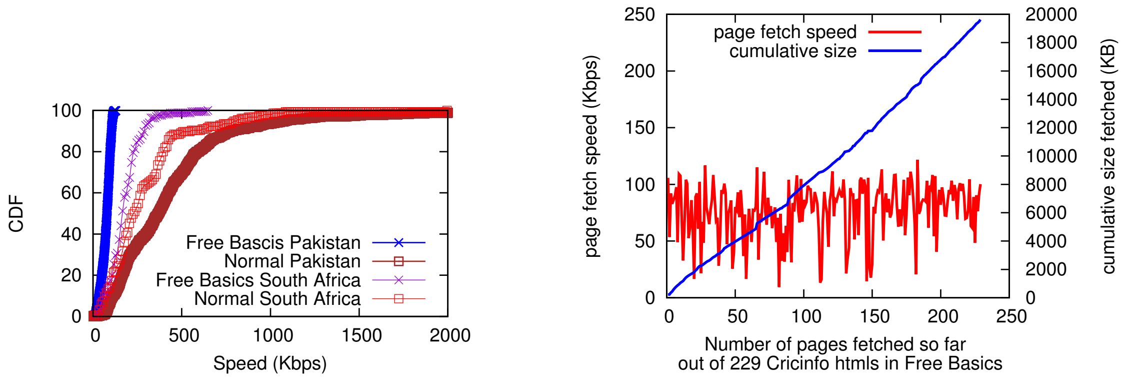
for last-hop router IPs to determine that the proxies for Pakistan were actually in Europe and those for South Africa were in the US.

Table 6.4 shows the ping latency from the client in Pakistan to the proxy, and also to the servers hosting the normal versions of BBC, Cricinfo and Mustakbil. As seen from the table, the delay to the Free Basics proxy was relatively high (300 ms), largely due to the proxy being located in Europe (about 5000 miles from the client in Pakistan). This delay was six times larger than the delay to cricinfo.com, which was hosted in Pakistan, and more than 50% higher than the latency to bbc.com (likely hosted in Asia). Interestingly, the delay to mustakbil was essentially the same as to the Free Basics proxy, likely indicating that the service was hosted in Europe. Similar differences in ping delays were seen in South Africa, between the Free Basics proxy and the direct access to bbc.com.

Taken together, the performance results indicated that Free Basics users saw poorer network performance to free sites than to paid ones. Whether this performance was tolerable to most users, and whether this was an acceptable price to pay for free service, requires further investigation with user studies and policymakers.

6.1.4.2 Does excess usage degrade download speeds?

Given that Free Basics was provided for free to the subscriber, this study investigated whether this was truly “all you can eat” or instead cellular service providers impose any usage caps. This would manifest in a degradation in network performance once a subscriber downloads sufficient Free Basics content. Figure 6.9(b) shows the network speeds for all pages downloaded for the Cricinfo service, with the x-axis being sorted in the order pages are downloaded. There was no significant downward trend over the one hour (consuming 19 MB). Thus, if there were any caps, they were triggered by either more time or more data consumed. The download requests, being script generated, were aggressive. Since such aggressive access did not seem to trigger any detectable throttling, a typical user might not see such effects, though this needed to be verified by actual usage.



(a) CDF of page fetch speeds

(b) Page fetch speeds over time

Figure 6.9: Network service quality of the Free Basics program, compared to the normal paid versions of the same services

6.1.5 Observation

Is gate-keeping by proxy necessary? One of the widely debated Free Basics design choices relates to the gate-keeper role played by Facebook. Though it is agreed that the technical specifications were well-justified (e.g. needed to make the services accessible to resource-constrained feature-phone users), it is unclear why these cannot be enforced by a basic transcoding proxy that strips web services of excess functionality (e.g. JavaScript) on the fly to match the desired technical specifications [143]. Such a design would have alleviated the need for individual web service operators to redesign their services and separately request Facebook to approve their services. From a user's perspective, such a design would tear down the wall around Free Basics services, make most traditional Internet services accessible, and significantly improve the user experience by limiting the number of broken (paid) links, when browsing (see Section 6.1.4).

While the transcoding proxy described above had the potential to open up the walled garden of Free Basics services, it might raise incentive concerns for network service providers (who might see a steep decline in the conversion rate of their Free Basics users to paid users[9]).

Furthermore, the decision to have all Free Basics traffic transit via the proxy raised two important concerns. First, as shown in Section 6.1.4.1, the proxies were often located (geographically) far from the Free Basics users and web servers, contributing to increased round-trip times and page download times for Free Basics users. Second, the proxy service provider had access to all, mostly unencrypted, end-user traffic. As an example of some of the potential privacy risks, the URIs exposed to Free Basics revealed information such as user locations (e.g. from weather query patterns in services like Accuweather) and political interests (e.g. from news browsing patterns in services like BBC). As the proxy provider, Facebook stated that they only inspect domain names and traffic volumes, and that they (curiously) store any cookies "in an encrypted and *unreadable* format" [143].

Is Free Basics violating net neutrality? Many have raised network neutrality concerns regarding Free Basics, most notably in India [141, 142]. This study found that in the two examples of Free Basics deployments that were analysed, traffic for Free Basics received much worse performance than normal (paid) Internet traffic; however, all content within Free Basics received the same performance.

6.1.6 Audit at Scale: Challenges

- For the measurements, mobile users with specific SIM card at the locations were required and through the collaboration with local researchers, 16 participants were recruited from several countries - Asia (6), Africa (6) and Americas (4). But most of these people were not technically proficient enough to set up desktop with Wi-Fi tethering and run scripts on the desktop or create remote login access, to be able to run desktop measurements, as operated in this study. A better option will be having an android app, that will be easy to install and run by these participants and which will do the measurements and send the data for offline analysis.

- Ideally, the android app should (a) launch the Free Basics website on the android phone browser, (b) gather the list of available services, (c) save the HTML of the service pages for analysis of the functional tags, (d) measure the network metrics like page load times and bytes exchanged for each service, (e) run the

[9]Facebook advertised the fact that nearly 50% of Free Basics users convert to paid Internet users within the first month of Internet use as an incentive for network carriers to offer Free Basics.

app iteratively and measure the network metrics for each iteration over time to detect throttling effects if any and (e) upload the measurement data to the server for offline analysis and comparisons across countries.

6.2 Quantifying performance gain from using Google AMP for content delivery

As reported by the Internet Society in 2015, the vast majority of content accessed by local users, in many developing countries and emerging regions, is hosted overseas. In many cases, the content must be accessed using international links and in sometimes under-provisioned networks [149]. Previous research has shown a strong link between local content, infrastructure development and access prices [23] and while it is known that local content can be a driver for increased global internet connectivity [150], performance and Quality of Experience (QoE) to access those content from developing regions still remain major issues [151, 152, 12].

In recent years, there have been many attempts by technology companies to deal with the problem of slow mobile web. For example, Facebook Instant Articles was introduced to make news stories load faster [153], while some browsers introduced proxy-based compression mechanisms (for e.g. Opera Mini, Flywheel) to improve the experience of users on slow networks [154, 155]. A particularly prominent technology that has recently emerged, is that of Google's AMP. AMP strives to reduce Page Load Times, by decreasing page size and complexity, whilst using its own Content Delivery Network (CDN) to distribute third-party content. Anecdotal evidence suggests that AMP has the potential to significantly boost web traffic and improve QoE [156]. It can be argued that these benefits will be particularly felt in developing regions, such as Africa, where connectivity remains challenging.

This thesis performed a first study of AMP-enabled web pages in Africa, by evaluating web performance when accessing local content, particularly local news websites. To achieve this, it first tried to understand the local content hosting situation in Africa. In order to shed some light on the distribution of local and remote hosting, a detailed analysis of where Africa's local content is physically and topologically located is provided. Such a study provides a deeper understanding of the content hosting challenges in developing regions, including the bottlenecks faced by local and global players in terms of infrastructure and QoS. Furthermore, the prevailing benefits of using the AMP platform for content delivery in Africa were analysed. In particular, this thesis sought to evaluate the extent to which AMP provides cheaper and faster access to information.

6.2.1 Accelerated Mobile Project

The AMP is an open-source web publishing platform, with the aim to improve web content delivery to end-users, specifically on mobile phone devices. It leverages several nascent web publishing [157] and compression technologies [158] to reduce page sizes and therefore allows considerable amount of bandwidth savings, especially for users on limited data plans. It also benefits from Google's very large networks of content caches around the world, therefore allowing AMP pages to be distributed on the edge, at faster download speeds. Figure 6.10 shows the workflow of an AMP page.

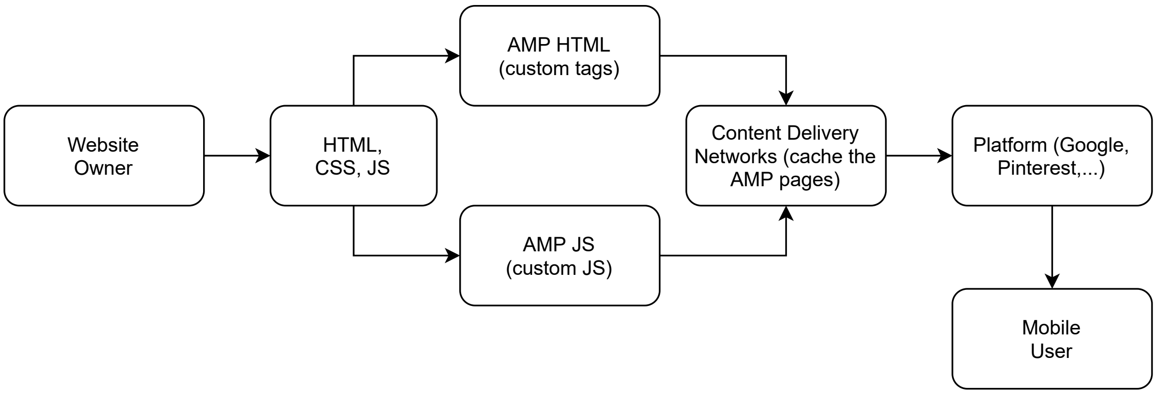


Figure 6.10: Google AMP Workflow

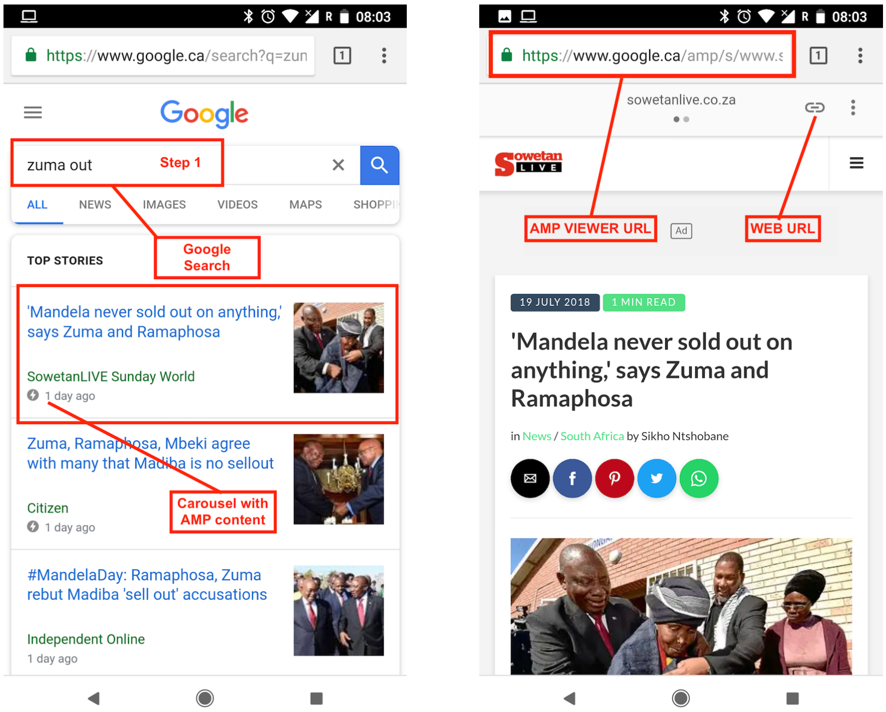
This section briefly describes how AMP works, explains the measurement methodology and describes the results.

AMP pages are essentially built around three main components:

1. **AMP HTML**: is an extended version of HTML to support AMP properties and it has some extra html tags such as *amp-img* or *amp-video*. It also has the *link* HTML tag which allow search engines to automatically detect AMP pages.

2. **AMP JS**: is the AMP JS library responsible for the fast rendering of AMP pages. It is also responsible for the optimisation and handling of external objects.

3. **AMP Cache**: The Google AMP Cache is a proxy-based content delivery network for delivering all valid AMP documents. It fetches AMP HTML pages, caches them, and improves page performance automatically. When using the



(a) Carousel (b) AMP Page

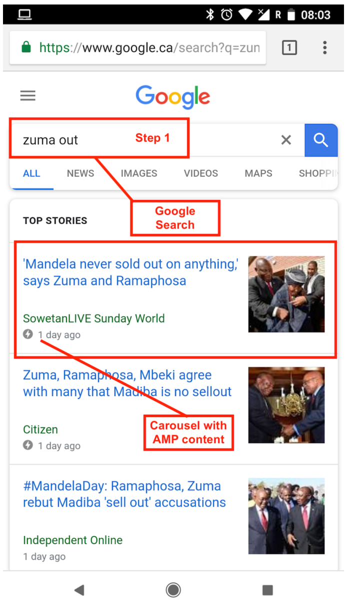
Figure 6.11: AMP interface on mobile phone

Google AMP Cache, the document, all JS files and all images load from the same origin that is using HTTP 2.0 for maximum efficiency.

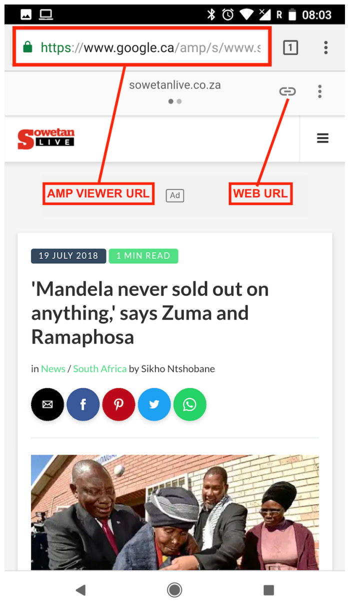
To be able to access an AMP page, a user typically needs to start with a Google search. The search engine will then provide a carousel (Figure 6.12) with a list of AMP-enabled websites - which can be identified by a *thunderbolt* sign. The AMP has essentially three types of URL which help to identify the AMP building block:

- **AMP URL**: The AMP version of the original web page, published and hosted by the content provider. This page has special AMP HTML tag and also maintains a link to the canonical source. URL: `https://www.example.com/amp/xyz.html`

- **AMP Viewer URL**: This is a copy of the AMP URL web content which has been crawled and cached by Google. They will usually be served from the different Google caches scattered around the globe. This is the URL which the end-user will be redirected to after doing a google search (for e.g. see figure 6.12.b). URL: `https://www.google.com/amp/s/www.example.com/amp/xyz.html`



(a) Carousel



(b) AMP Page

Figure 6.12: AMP interface on mobile phone

- **AMP CDN URL**: This URL is usually hidden from the end-user. After the crawlers have retrieved the AMP URL, objects from the AMP page are stored on the AMP project CDN. URL: `https://www-example-com.cdn.ampproject.org/c/s/www.example.com/amp/xyz.html`

In this study, the Page Load time between AMP URL, AMP Viewer URL and normal web pages were compared.

6.2.2 Methodology

The performance of websites is defined by a mix of the underlying infrastructure (e.g. network and servers) and the structure of the web content itself. Before moving onto exploring AMP (which modifies the web content), the study first inspected the available content hosting infrastructure and location. It looked at both QoS by measuring the Round-Trip Time (RTT) and the number of intermediate hops (traceroute) to the news websites and QoE was measured by running measurement on the page load time on both AMP and non-AMP web pages.

6.2.2.1 Selection of websites

To measure web performance, it is first necessary to select a set of websites. To this end, a list of 1413 news websites from 54 different countries were compiled directly from ABYZ News Links, last accessed 2020-02-11, http://abyznewslinks.com/. The study focused on news sites, as it was possible to gain ground-truth on their locations; thus avoiding Alexa rankings, as these mostly contain international, rather than local websites (e.g. Google, Facebook, Twitter etc).

The study therefore restricted the analysis to news websites obtained from the ABYZ News Links directory. The directory does not rank the sites, but rather attempts to list all the prominent media sites for each country. News websites were chosen as they represent content of local interest with regards to the country where the reader base is located, but also because AMP is very popular amongst news publishers.

6.2.2.2 Measurement platforms

Once the list is compiled, it is then necessary to launch performance measurements towards their respective host or domain. Specifically, the study is interested in understanding which paths packets are taking (*traceroute*) and how long it takes them to move from $A \rightarrow B$ (latency). For this, the RIPE Atlas platform was useful. Additionally, to evaluate the impact of the hosting locations on performance from an end-user's perspective, Page Load tests using the Speedchecker platform were performed. It is important to note that the tests were run from probes in the countries where the news website was local to, such that the results are as close as possible to the end-users' experience. Below is the three platforms used:

- **RIPE ATLAS:** is a global, open and distributed hardware-based platform made up of more than 10,000 probes around the world. At the time of the experiment, 196 RIPE Atlas probes were used from 37 countries. (See section 2.3.1 for more details)
- **SPEEDCHECKER:** is a commercial software-based platform running on PC, Android and DD-WRT routers (See section 2.3.2 for more details). It provides an API for Page Load tests, from which the following metrics could be obtained:
    1. **Page Load Time (PLT)**: is time it takes between the first initiate request and when the page is fully loaded.
    2. **Time to First Byte (TTFB)**: is the time taken for a browser to receive the first response byte from a server.
    3. **DNS Lookup Time (DNSLT))**: is the time it takes for the probe to complete a DNS resolution for the domain.

4. **SSL Negotiation Time (SSLNT)**: is the time it takes to initiate and complete a full Secure Sockets Layer (SSL) handshake.
5. **Initial Connection Time (ICT)**: is the time it takes establish a Transmission Control Protocol (TCP) connection (i.e. a full handshake)

PLT consists of: (1) *network time* (ICT, DNSLT, SSLNT) (2) *browser time*, which is the time it takes to download web objects and process the Document Object Model (DOM) and render the page. PLT is therefore the overall QoE metric being evaluated in this experiment.

- **MAXMIND[10]:** is a geo-location database which provides an IP to Location mapping. With this, the network or country of a server could be determined.

6.2.2.3 *"traceroute"* dataset

The study worked with a corpus of 1413 websites in Africa as extracted from http://abyznewslinks.com. RTT measurements were carried out on on 1191 websites from 37 countries, the remaining websites being non-responsive. The *traceroute* measurements were repeated over a five-day period, resulting in about 19,299 successful measurements between the probes and the websites. Each *traceroute* measurement returns three final hop RTTs, meaning that in total, there were 57,897 end-to-end RTTs. However, the number of domains probed in the Page Load test, as explained below, was much lower than in the *traceroute* dataset, as only AMP-enabled domains were measured.

6.2.3 AMP-enabled news article links

Before performing any page load tests, the measurement script scraped the 1191 active websites, and looked for a special `<amphtml>` tags, i.e. only AMP-enabled web pages. Figure 6.13 shows the distribution of AMP and non-AMP news websites in Africa. In the end, only 16% of active news websites were found using AMP in Africa. More specifically, there were 194 AMP-enabled news websites in 22 countries.

As the number of article links varied by website varies considerably, a random list of 10 AMP-enabled web articles were selected (per news website) that were found during the scraping process. This sampling produced a dataset of 1477[11] individual URLs, on which Page Load tests both on the normal web pages and their equivalent

[10] MAXMIND IP Geolocation, last accessed on 2021-04-28, https://www.maxmind.com
[11] Some websites had less than 10 article links when scrapped

AMP page were run. So the total number of individual pages probes were 4431 for the three types of URL.

6.2.3.1 *"Page Load"* tests

The SpeedChecker platform provides an API which allows you to select a destination (URL) and a set of probes from which the measurements are launched. For this experiment, only probes running on Android devices were selected. It is important to note that SpeedChecker only provides access to Android probes running on Wi-Fi only. Each measurement request to the platform provides results from a maximum of 10 measurement points, selected randomly from the available pool. Additionally, the whole set of Page Load tests (on the three types of URLs) was repeated at five different times, during a week, before aggregating the results. From the 4431 different URLs measured, the study generated a total of 9224 measurements data points i.e. measurements were done from an average of two probes for each URL.

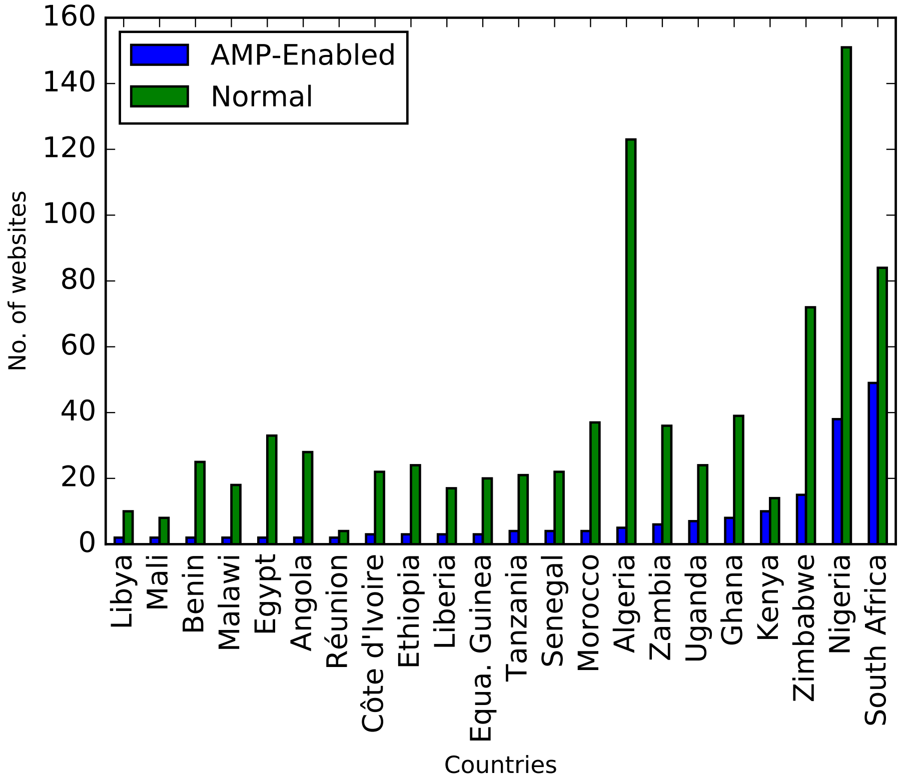


Figure 6.13: Distribution of AMP-enabled vs non-AMP websites in the subset of websites selected for this study.

Table 6.5: Summary of measurements obtained

Data collected		Traceroute	Page Load
# of domains		1191	194
# of countries		37	22
# of ASNs		223	51
# of unique web pages		-	1477
# of URLs probed Original/AMP Viewer/AMP CDN		-	4431
RIPE Atlas	Probes	196	-
	Measurements	57,897	-
Speedchecker	Probes	-	225
	Measurements	-	9224

6.2.4 Measurements and results

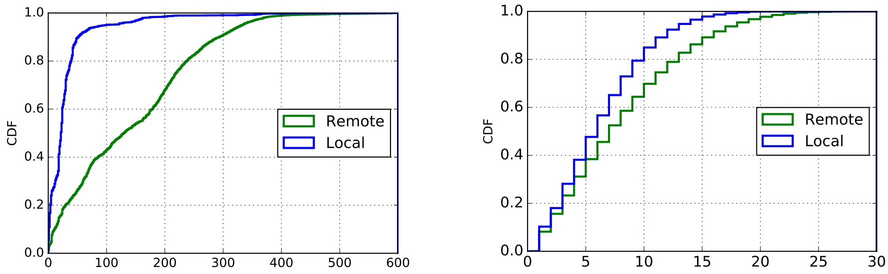
This section describes both the *traceroute* and *page load time* measurements to the local news websites, which helped to reveal information such as latency and geolocation of content servers. The study first compared URL types i.e. AMP vs non-AMP pages and then the regions of access by running the page load measurements from EU, US and Africa to understand the impact of remote hosting on QoE, on accessing the news websites. The full set of page load measurements were repeated five times and each API call produced 10 page loads data points.

6.2.4.1 Routes to reach news websites

With the 57,897 trace paths obtained (including RTT values), the median latency for locally-hosted websites versus remotely hosted websites was calculated (see Figure 6.14.a). As expected, the cost in terms of latency to reach a remotely hosted website was much higher (by seven times). This was also confirmed by the number of intermediate hops as in Figure 6.14.b, which was slightly higher for remotely hosted websites, as the use of international connectivity brought in added delay [151]. It is argued that usage of AMP can potentially change this situation, as AMP pages can be served from Google AMP caches (GGC), which are found in most major locations in Africa[12] or from Cloudflare AMP caches[13], the current two AMP cache providers.

[12]Google Peering Infrastructure, last accessed on 2021-01-29, https://peering.google.com/#/infrastructure

[13]Cloudflare AMP Caches, last accessed on 2021-01-29, https://amp.cloudflare.com/



(a) Median RTT (ms)

(b) Intermediary hop count

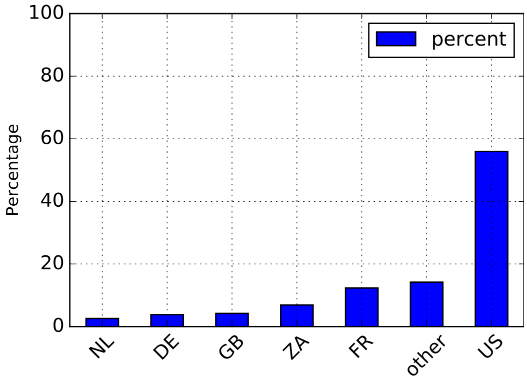
Figure 6.14: Median latency to remotely hosted content is seven times longer than locally-hosted content

6.2.4.2 Location of hosting providers

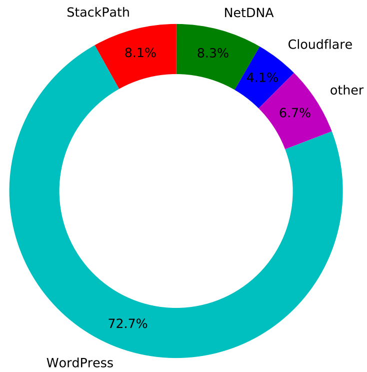
From Figure 6.15.a below it can be observed that the US took the lion's share in hosting African content, with about 56% of all the websites being hosted by American companies. Within Africa, South Africa was leading in the content hosting business, hosting about 7% of all of Africa's remotely hosted news websites (i.e. minus those that belong to South Africa). The rest of the websites, about 25%, were hosted in various countries in Europe. As previously mentioned, having content hosted remotely adds to the overall page load time and therefore can impact negatively the overall quality of experience of a user. This is what AMP aims to tackle by reducing web site complexity and load times. Section 6.2.6 studies the difference in page load time when African content is accessed from Europe or US as opposed to from within Africa itself. The same study is repeated on AMP-enabled web pages to compare and contrast (see figure 6.18).

6.2.5 Distribution of content networks

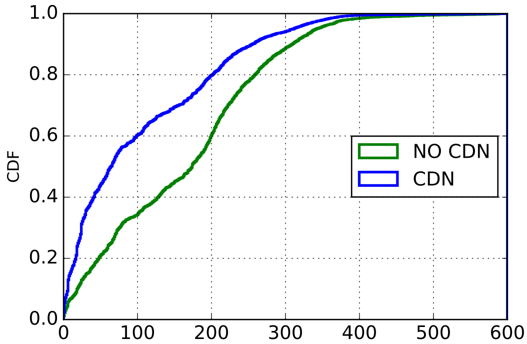
Similar to the geolocation analysis, network-level analysis showed that most of the websites were hosted by foreign companies. In total, all of 1191 news websites were scraped and the images, javascript, video and audio files were retrieved from their main page. In total, 57,444 objects were downloaded as shown in Table 6.6 amounting to ≈2GB of data. As expected, images represented a larger share (78%). To understand where those objects were hosted, this study analysed the URLs of the objects and retrieved their domains (e.g. *fbcdn* is for Facebook, *wp.com* is for Wordpress). Without much surprise, Wordpress (US) takes the biggest share of the market, hosting about 72% of the websites, followed by NetDNA (8.3%), StackPath (8.1%) and Cloudflare (4.1%). Data from Google and Facebook were removed as they



(a) Host countries



(b) Hosting providers



(c) RTT (ms) with CDN usage

Figure 6.15: Content hosting and distribution

were mostly pointing to ad-related objects and therefore skewed the results. Otherwise, Google represented 23% and Facebook 9.7%, which were mostly consisted of javascript documents and Facebook platform images. This correlates with the finding on the geolocation of the domains, which is mainly dominated by the US, where Wordpress is predominantly hosted.

Table 6.6: Number of web objects collected on main pages

Object type	**Amount**	**Size (KB)**	**Percentage**
image	46200	1699477	78.9
script	13072	416825	19.35
video	17	409	0.01
audio	5	36970	1.71

What is important to note is that the leading content hosting providers for Africa's remotely hosted news websites were largely based on Cloud infrastructure and make use of CDNs. For example Cloudflare, Akamai, Microsoft Azure, Amazon have their Points of Presence (PoPs) in multiple places in Africa. Wordpress is currently the most used Content Management System (CMS) in the world (60%) and this might explain why Google has strategically partnered with Wordpress to disseminate AMP pages using the CMS plugin.

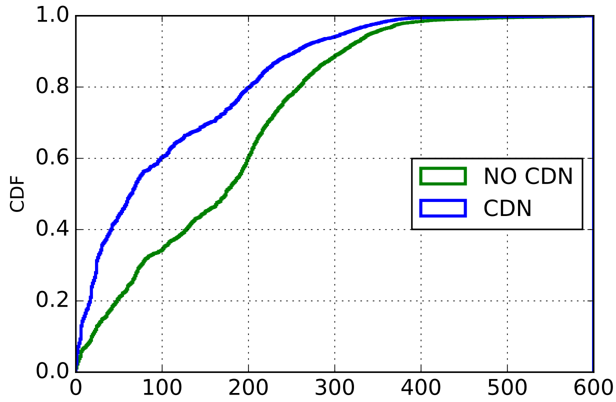


Figure 6.16: Benefit of using CDN for local content hosting

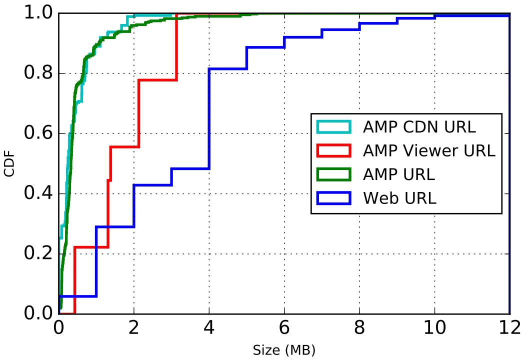
From a performance perspective, Figure 6.15.c shows that there is some benefit of using CDN to host local content as, in doing so, it reduces the latency to the content by a factor of two. Domains using CDN were identified by the domain name in their URL, the network name of their Autonomous System Number (ASN) also revealed which CDN was currently hosting the website. Having content closer to the edge is therefore what content providers should be aiming for. Google AMP currently uses two AMP Cache provider namely Google AMP Cache and Cloudflare AMP Cache. The platform automatically chooses from which cache provider the content should be served. This study therefore uncovered how Google AMP project is leveraging their global CDN infrastructure to provide low-delay access to content.

6.2.6 Measuring web quality of experience

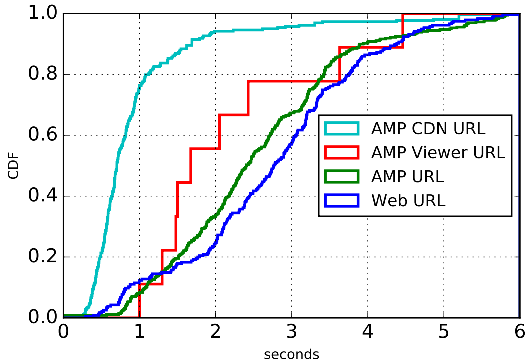
This section describes the results obtained from measuring the *Page Load* dataset. Firstly, the aim of the experiment was to understand the difference in Page Load time between the different URL types (AMP URL, AMP CDN URL, AMP Viewer URL and WEB URL[14]) and secondly, there was a need to understand the difference in QoE for a user located in Africa as opposed to being located in the US or EU, where most of the African news content are actually hosted. For the latter, the Page

[14] **Web URL** refers to The canonical (original) web page that is published and hosted by the content provider. This is a normal HTML web page which has a special reference to an AMP version of the same page. If the page contains an *amphtml* tag, it means there is a corresponding AMP page. URL: `https://www.example.com/xyz.html`

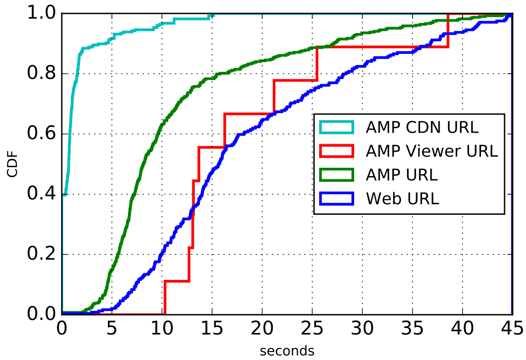
Load tests were run for the **WEB URL** and their equivalent **AMP Viewer URL**[15], using probes in EU, US and Africa.



(a) Page Size



(b) Time to First Byte (TTFB)



(c) Page Load Time (PLT)

Figure 6.17: Larger page size, TTFB and PLT for WEB URL

COMPARING URL TYPES:

Page Size: Figure 6.17.a describes the differences between the three URL types in terms of page size. As expected, a clear difference in page size between WEB URL and AMP URL could be seen, confirming that AMP stripped down or compresses many objects before rendering. In 80% of the pages explored, AMP pages were 8x smaller than normal web pages. As seen below, this definitely had a positive impact on the overall Page Load time.

TTFB: As it can be seen from figure 6.17.b, the TTFB (i.e. latency) for AMP CDN URL was much smaller than AMP URL, AMP Viewer and WEB URL. As AMP CDN URL was served from an edge location (for e.g. Google or Cloudflare), this explains why latency to reach the content was almost three times smaller. It can

[15]The AMP Viewer URL was chosen as point of comparison as it is the URL that the user will navigate to after doing a search on Google.

also observed that AMP URL and Web URL had more or less the same TTFB, as both web pages were hosted on the same server.

PLT: Figure 6.17.c is a CDF of Page Load Time where it can be observed that the fastest is AMP Viewer URL. One main challenge with measuring Page Load time of the AMP Viewer URL, was that Android Speedchecker probes in Africa are scanty, leading to some skewness in the data. On the other hand, there was a better distribution in the EU/US measurements. Additionally, it was observed that on average, an AMP URL would take around 10s to load while it takes 17s for a WEB URL to load.

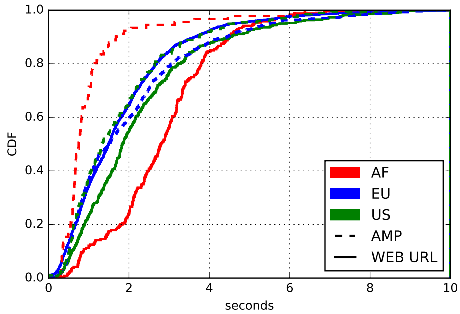
COMPARING REGIONS OF ACCESS:

TTFB: Figure 6.18.a is a CDF of TTFB that had been collected using probes from Africa, Europe and the US. As it can be seen on average, it was faster to access African content from EU or US than from Africa itself by a factor of 1.5. This is a well-known situation which can be due to many factors as explained earlier such as circuitous routing or remotely hosted content. However, with regards to AMP, access to the first byte was much faster in Africa than from EU or US. This perhaps may have to do with the fact that AMP pages were hosted on Google caches, located within an ISP in the country or close by.

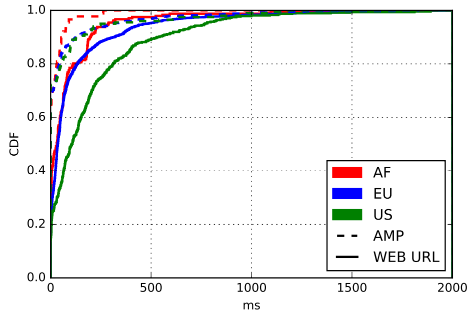
PLT: PLT is the most important metric in this analysis as it is a proper indication of QoE. It is a function of the DNS Lookup Time and SSL Negotiation Time, the latency to the server (≈TTFB) and the amount of data that need to be download. Besides, Page Load time can also be influenced by the link quality (throughput, congestion, jitter, etc.). In figure 6.18.b, it is very clear that loading AMP was faster than loading normal pages, across the three regions. The plot also shows that normal pages were loaded faster in the EU/US than in Africa (at least by 1.5x). With regards to AMP, it seems to be faster to load an AMP page from Africa than from EU/US.

DNS Lookup Time: Figure 6.18.c shows that it was generally faster to resolve DNS queries on AMP, but it is interesting to note that it was faster to resolve the domain names from Africa than from the US. An explanation could be that DNS resolvers in Africa already cached the domain (as they are from Africa) as opposed to resolvers in the US.

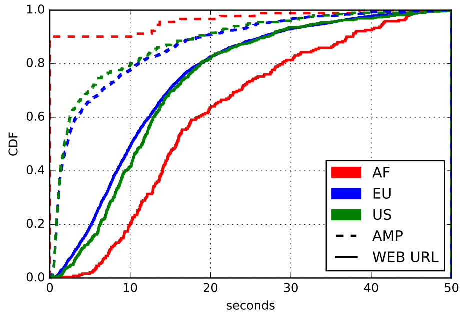
LOCATION OF AMP CACHES: To supplement the analysis in the previous section, traceroute and reverse DNS lookups were used to determine the location of the Google AMP caches as they would be accessed from the 22 countries in the AMP



(a) Time to First Byte (seconds)



(b) DNS Lookup Time (ms)



(c) Page Load Times (seconds)

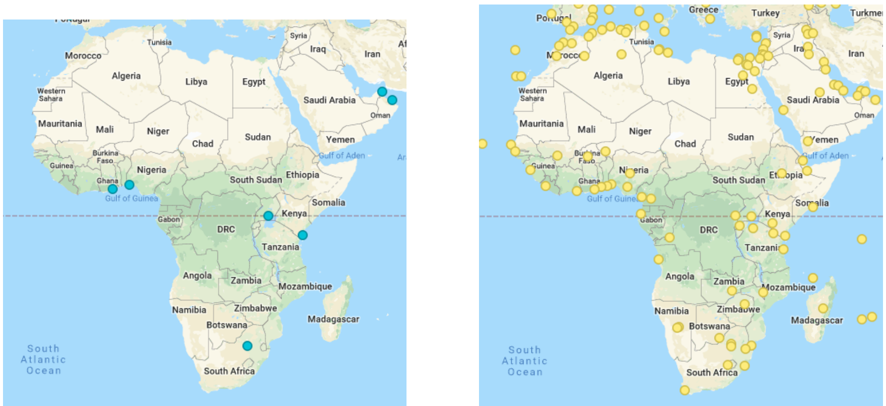
Figure 6.18: Page Load Times much higher from Africa (50% larger than 30sec), but lower using AMP (80% lower than 10sec)

study. Google AMP caches shared the same domain name `cdn.ampproject.org` and the caches were hosted by anycast servers using the same range of IP addresses. To determine those locations, the study performed a traceroute measurement campaign[16] using RIPE Atlas from 19 countries (no probes were available from Liberia, Equatorial Guinea and Mali at the time of the experiment). Each AMP cache had a reverse DNS domain for e.g. the Mombassa cache is `mba01s08-in-f1.1e100.net`, where *mba* is the airport code. Figure 6.19 provides an indication of the location of the caches.

It was observed that AMP pages from Eastern and Southern Africa countries were predominantly fetched from Mombassa, Northern Africa from Milan, Frankfurt and Marseilles and Western Africa from Frankfurt and London. Two interesting cases were found: Ethiopia fetching content from Stockholm and Angola from Washington DC, with relatively higher latencies. Formoso *et al.* also found the same exact two countries which did not share the same latency characteristics as other neighbouring countries [152]. The reasons were that Angolan ISPs usually peer with networks where Portuguese content was hosted (Brazil or Portugal) and the fact that Angola

[16] Collect 2437 traces using 58 probes from 19 countries

is well connected to the US through the undersea cable[17] via Brazil. Ethiopia had only one incumbent operator and international connectivity are sometimes carried out using satellite links.



(a) Google POPs (b) Google Cache

Figure 6.19: Location of Google caches (GGC)

Another notable observation is that Nigeria was hosting a Google AMP cache and latency from within the country was very low (1.434ms). But none of the other Western African countries in the study were fetching content from Lagos. This again proved a lack of coordination and peering in the Western African region, as explained in Chapter 7.

OBSERVATION: The study clearly showed that PLT of WEB URLs are higher, when news websites are accessed from Africa as opposed to from US and EU. This corroborates with the findings on the location of the content itself which confirmed that hosting in the US and in the EU, had indeed an incidence on the overall PLT. The median PLT in Africa was 15s vs 10s in Europe or US. However, it can also be seen that their AMP equivalent pages have a much smaller PLT. There was a 80% reduction in PLT for webpages on AMP. The benefits are particularly pronounced in the Africa measurements, which on average save 12s vs. 8s in Europe, between AMP and non-AMP pages.

Through the above, the study gives an overview of the current content hosting situation in Africa. Because of a lack of infrastructure and proper incentives to host local content locally, most of Africa's local content today is hosted in remote locations. Even if there is more and more deployment of cloud service providers in Africa, it can

[17] Telegeography Submarine Cable Map, last accessed on 2021-03-12, https://www.submarinecablemap.com/

Table 6.7: Location of AMP Caches when accessed from selected African countries

Source Country	**AMP Cache Location**	**Average Latency (ms)**
Nigeria	Lagos	1.022
Tanzania	Mombassa	6.262
Kenya	Mombassa	6.581
Uganda	Mombassa	15.344
Algeria	Milan	33.638
South Africa	Mombassa	46.457
Zimbabwe	Mombassa	68.419
Libya	Frankfurt	80.021
Egypt	Marseilles	80.141
Morocco	Marseilles	86.705
Malawi	Mombassa	91.684
Senegal	Frankfurt	104.025
Cote D'Ivoire	Frankfurt	139.215
Angola	Washington DC	192.245
Benin	London	195.214
Ethiopia	Stockholm	207.943
Reunion	Amsterdam	211.792
Ghana	London	236.224

be seen from the plots that it is still slower to access content from a remote location, than from Africa itself. Hopefully, the situation will improve over time as more CDNs will deploy their PoPs in Africa.

6.2.7 Is AMP a viable alternative?

The study showed that there is indeed a benefit of using AMP as a means of content delivery, especially for users in developing regions. By reducing the size of the page, users on limited data plans can also save on expensive mobile data usage [159]. AMP is therefore a promising web publishing technology that not only is beneficial for the end-users but also allows content publishers to increase their reach and maintain their reader base.

However, AMP comes with a lot of controversies. It forces end-users to remain within the Google's domain and as a consequence it diverts traffic towards websites hosted by Google [160]. At a scale of billions of users, AMP would reinforce Google's dominance in the web as it can be potentially considered as the *de facto* mechanism for fast content delivery. The fact that third party content is now within the realm of

Google, the search engine can choose to prioritise which content end-users should see first, at the detriment of non-AMP enabled web pages. This situation further raises questions of centralisation of data and search neutrality [161].

The success of the World Wide Web and the Internet is due to consensus building around open standards developed by the World Wide Web Consortium (W3C) and the Internet Engineering Task Force (IETF). Web acceleration technology, like AMP, should be no exception and should ideally become a protocol adopted and developed by the W3C. At a minimum, web acceleration technology should be made available as open-source technology that can be deployed in ISP DMZs or locally-owned community networks and adapted to local needs. Examples of open-source web acceleration are Ziproxy[18] and Varnish[19]. One of the challenges is that these solutions cannot currently handle HTTPS. Accelerating content that uses HTTPS would require trusted edge caching services where content providers can place their content closer to the user edge of the network. These edge cached services could then run web acceleration technology such as AMP or Ziproxy to further accelerate this content to users if necessary. With web acceleration being in control of the ISP or community network, acceleration parameters could be tuned to the users preferences or network conditions.

6.2.8 Challenges and limitations

Some of the challenges faced were: some websites were not responsive and had to be removed from out initial hitlist. Scraping the websites to retrieve news articles (only) was challenging as content organisation differs from website to website. Furthermore, this study is limited by a few factors. The Speedchecker platform is a software-based platform, where probes are running on end-users' mobile phones or PCs. This makes the number of active probes very volatile. Therefore, the experiment was run multiple times to make sure enough measurement data points were made available for analysis. Another issue was the number of active probes in Africa, which was far less than in other regions. There were also very few Android probes on the platform in Africa, which explains why some results were a bit skewed. Finally, Speedchecker did not provide the HAR (HTTP Archive) files associated with the Page Load time test; this would have enabled a more in-depth analysis of the internals of AMP. There was also a disparity in the dataset between the number of traceroute (1191 data points) and page load (194 data points) measurements. Page Load, being very resource-intensive,

[18]Ziproxy, last accessed on 2021-02-05, https://en.wikipedia.org/wiki/Ziproxy
[19]Varnish Cache, last accessed on 2021-02-05, https://varnish-cache.org/

were more scarce than traceroute. This might have had an impact on the page load results.

6.3 Conclusion

This chapter presented a QoS analysis of the Free Basics application by analysing the available services and their functionalities. It analysed the network architecture and policies responsible for the observed network QoS, and also the mobile device capabilities from which the service requests come. As shown in the experiments, Free Basics services can see 4-12 times worse network performance than their paid counterparts and there are multiple factors contributing to this performance gap. Additionally, there is a significant point of concern against the Free Basics program is the unfair advantage free web services have over their paid counterparts, violating net neutrality [162]. This implies that the net neutrality debate should be more nuanced than the "free gets advantage" arguments, asking additional questions like "free, but with what constraints?". Adding data to this debate will need measurement of services within and outside the Free Basics program, and possible comparison of their temporal growth in user base, keeping other factors constant. Or a survey among users to see their relative use of Free Basics vs. paid services.

Next, this chapter evaluated the performance impact of Google's AMP in Africa. It analysed the hosting situation of 1191 African news websites, focusing on metrics such as RTTs and number of hop between African vantage points and the websites, hosting countries and networks, pages sizes, and page load times. It further performed an analysis on 194 of the 1191 websites that were found to be using the AMP infrastructure by comparing access via AMP and traditional web hosting. The results indicated a significant reduction in website sizes as downloaded onto web clients by a factor of 8. This reduction can make for significant savings in data costs for Internet users in Africa, especially for mobile Internet users. In terms of performance, our results indicate that page load times are much higher in Africa compared to EU and US (50% of website load times in Africa are over 15s, compared to EU/US where 70% of pages load under 15s), but significantly lower using AMP (80% lower than 10sec). When AMP is used, there is a significant improvement in page load, with over 80% of the pages loading under 10s. While AMP's performance improvements in Africa are obvious, further discussion needs to be had in terms of how the platform promotes externalisation of Africa's local content. The findings would allow to better understand the current underpinning of local content generation and consumption in developing regions and the hegemony of some “big content providers” in the race to host local content.

Chapter 7

Characterising Latency in African Networks

The studies in the previous chapters have analysed how the Internet is being used and consumed in different African countries and how access to local content and cloud computing services are still important obstacles to lower the barrier (in terms of performance and cost) of Internet access in Africa. This study performs a deep-dive into the infrastructure that connects African countries by evaluating the inter-country latencies in Africa. It quantified latencies across 91% of African countries, and have identified a number of failings in the regional topology that would require improvement.

7.1 Introduction

Africa currently has the lowest rate of Internet penetration in the world [163], with many unable to afford access [164]. This is set to change with Africa predicted to be a major driving force in expanding global uptake. Despite this, recent studies have observed generally poor performance on the continent, *e.g.,* slow page load times [89]. Although the exact causality is yet to be seen, there are a number of general trends that can be highlighted, including the use of high-delay access technologies and suboptimal country-level topologies [21].

This study argues that understanding and quantifying these issues is critical for not only their short-term amelioration, but also for informing future design and deployment strategies, *e.g.,* for CDNs in the region. Importantly, the underdeveloped (but rapidly expanding) nature of Africa's Internet ecosystem means that this must be done *now*.

Although there have been a number of seminal studies that have explored global Internet performance and topology [165, 166, 167], the diversity of networking infrastructure across Africa makes them largely inapplicable. Of particular interest is the means by which the countries of Africa are interconnected; only by improving this can a local Africa-wide Internet ecosystem flourish. For example, the deployment of much-needed African data centres depends on underlying connectivity to make them available to the wider region [29].

Thus, this chapter asked a simple question: *What is the inter-country delay in Africa, and how is this impacted by topology and interconnection strategies?*.

Answering the above question, however, required vantage points across Africa — a challenge which has prevented many studies from focusing on Africa. Hence, this study exploited a new platform, *Speedchecker* (a commercial measurement service), which had around 850 probes in Africa, covering 322 networks in 52 countries (§7.2). The measurements revealed a highly uneven delay distribution, with some countries exhibiting European-like delays (*e.g.,* South Africa → Botswana takes 25ms), whilst others suffer from delays exceeding 300ms (going up to 900ms).

For context, typical latency in North America is <45ms and <30ms for Europe [168]. This lead this study in exploring patterns and cluster countries into groups of high connectivity (§7.3). This revealed distinct geographical patterns, as well as a number of corner cases, where more distant countries actually have lower delay than nearer countries (§7.4).

It was found that some countries and regions have built up relatively low delay infrastructure, although many others have not. To explore this, the study inspected the continent's topology to identify key issues in the region (§7.5). It was observed that the use of intercontinental transit (rather than local interdomain peering) played a key role in inflating delays. This saw Africa→Africa packets leaving the continent via international transit, simply to re-enter again in a circuitous manner. In general, this situation dramatically increases network operator costs, due to the high prices charged for international transit [169]. It also makes certain common infrastructure deployment practices unworkable, *e.g.,* it makes little sense to deploy content servers at regional exchange points if networks do not peer there [89]. Whereas the study quantified the delay impact these decisions had, there were observed cases in which using European or American upstream providers actually results in *better* performance than using African upstream networks. Such observations best highlighted the immediate challenges in the region, and helped explain the difficulty in accessing and deploying services on a continent-wide basis (as exemplified by several studies [170, 159]). The findings in this chapter offer insight into how these problems can be addressed.

7.2 Data Collection

7.2.1 Measurement platform

Collecting data samples that properly represent regional connectivity was not trivial, as it required multiple vantage points located in a diverse set of networks, as well as performing measurements to many target networks. Due to the deficit of research infrastructure in Africa, there were only two feasible platforms for launching the measurements: (*i*) RIPE Atlas, which is known for providing a worldwide network of physical probes to their members; and (*ii*) Speedchecker, a platform consisting of software agents installed on desktop clients. The Speedchecker platform offers Internet performance monitoring through ICMP ping, DNS and traceroute. Both platforms have probes deployed in Africa. At the moment of writing, RIPE Atlas had 229 active probes in Africa, covering 36 African countries, whilst the Speedchecker platform has nearly 850 installations covering 52 countries (see figures 7.1 and 7.2).

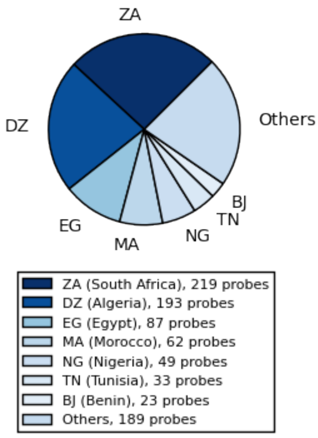


Figure 7.1: Probes count by country

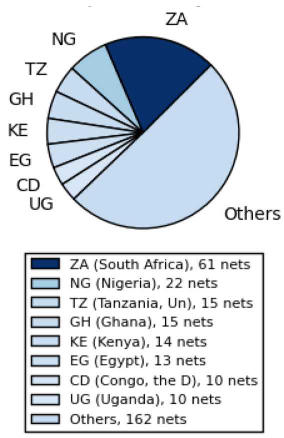


Figure 7.2: Amount of networks covered by country

Unfortunately, RIPE Atlas also had a strong bias towards academic networks, as well as around half of all probes hosted in South Africa. In contrast, Speedchecker covered 91% of African countries and was not biased towards university networks. Hence, for this study, Speedchecker was selected.

It should be noted that using other global measurement platforms and datasets (*e.g.,* CAIDA's Ark) would be unsuitable as they have few vantage points in Africa and therefore can only trace paths routes *into* Africa — not within the continent.

To evaluate the platforms' performance, the study launched the same experiment in both platforms, from the same networks, over the same time period, and compared the results. Figure 7.3 shows a histogram of the RTT difference between samples launched from the same network, where it can be seen the platforms' performance similarities: RTT differences were centred mostly around 0 ms, and had a std. dev. of 78 ms, meaning that 68% of samples were distanced by 78 ms or less. This similarity was interesting provided the two platforms run over very different paradigms: while Atlas is hardware-based and connected through cable, the virtual platform is based on software agents. Even after smoothing the curve (KDE line), most of the differences are concentrated around the 0 ms mark, confirming the above observation.

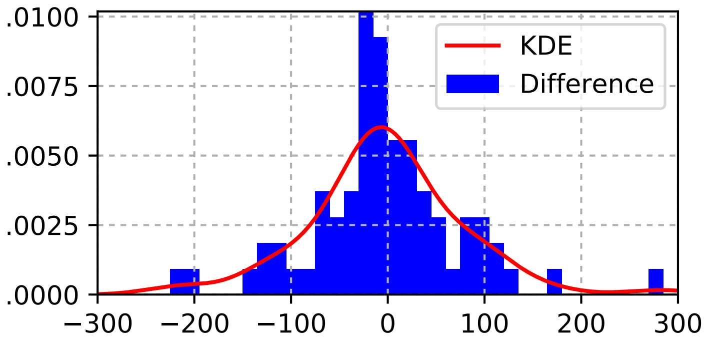


Figure 7.3: Comparison between RIPE Atlas and Speedchecker

7.2.2 Datasets

Speedchecker was used to collect two core datasets based on latency and topology measurements. The study chose to focus on these low-level metrics as they can be used to shed insight on how various applications might perform, *e.g.,* web, gaming. Latency data was collected by launching pings from *all* Africa-based Speedchecker probes to randomly selected Speedtest servers located in African countries. There were 213 Speedtest servers in Africa, covering 42 countries (from 54). Note that this means there were countries with sources (Speedchecker clients) but not destinations (Speedtest servers). In these cases, the intra-country delays could not be computed, and therefore were excluded from further analysis. Speedtest servers are generally hosted by ISPs and are therefore perfect end-points for network to network latency profiling. Full details about the service and its locations can be found online.[1] The

[1]Ookla Speedtest platform, last accessed on 2021-04-28, `http://www.speedtest.net/`

measurements were launched four times a day, at 00:00, 06:00, 12:00, and 18:00 probe time.[2] In each case, up to 20 probes from all countries in that time zone were randomly selected. These probes were then instructed to launch 10 consecutive pings (one second apart) to their randomly chosen Speedtest server. Following this, the Speedchecker API returned the minimum ping delay observed, giving the "best" observed delay at that time period.

By repeating this each day for 3 months, delay measurements across the continent were garnered, consisting of 42.2k ping samples. To quantify the coverage, Figure 7.4 presents the percentage of networks that the Speedchecker probes covered across each country (taking the overall count from the AFRINIC allocation files). In total, the data covered 319 networks across 52 African countries. 50% of the countries had at least 20% of their networks probed.

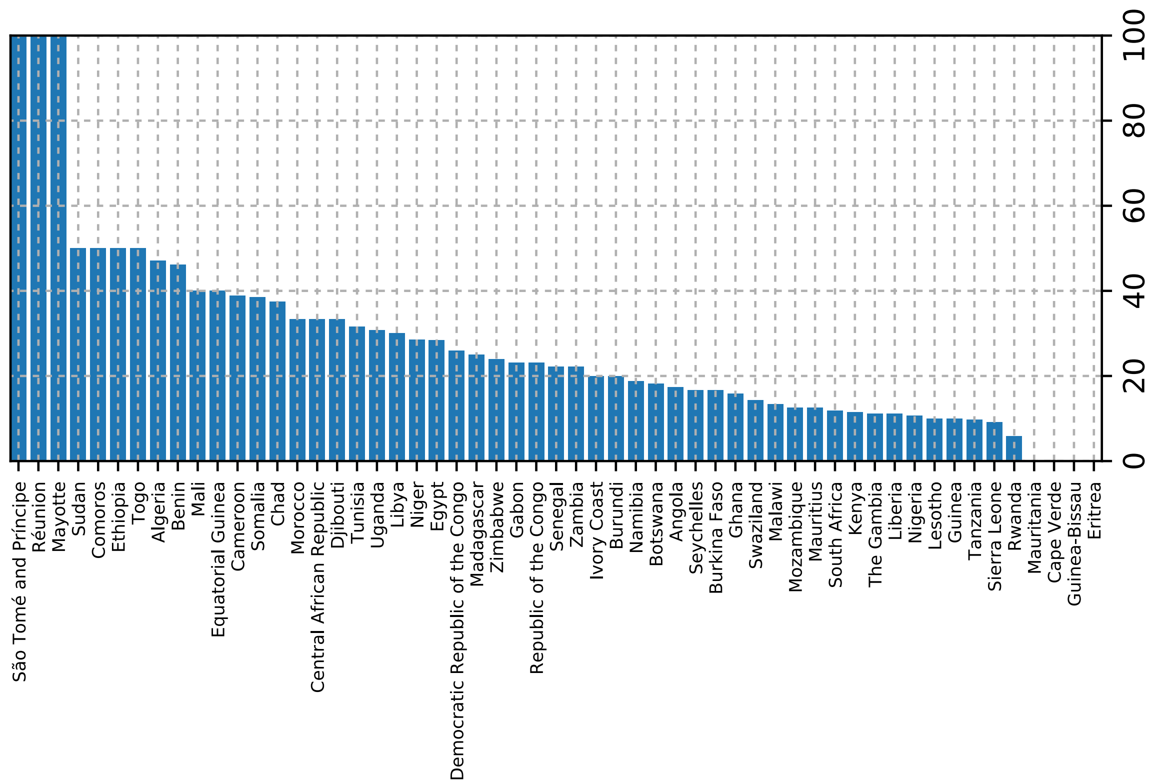


Figure 7.4: Percentage of Autonomous Systems covered per country by the measurements

The samples were filtered with the interquartile range, criteria in order to strip out potential outliers. To complement the raw delay measurements, this study also launched a parallel traceroute campaign using the same setup. At 00:00, 06:00, 12:00,

[2]Note that the times were based on the local time zone

and 18:00 local time, traceroutes from up to 20 random probes in that timezone were launched, targeting random Speedtest servers across Africa. This campaign covered 49 countries, and consisted of 31.5k traceroute measurements from 207 distinct networks. For each router hop within the traceroute data, the Autonomous System Number (ASN) was retrieved, using the RIPE Routing Information Service.[3]. The location of each router was also derived, using MaxMind GeoLite2-City. The study was restricted to country-level analysis, as this was found to have relatively high accuracy [132].

7.2.3 Data filtering performed based on RTT asymmetry

An initial exploration of the RTT dataset revealed one particular characteristic: the RTTs between countries were by no means symmetrical. Measurements originated in country A and targeting country B, were not necessarily similar to those originating in B and targeting country A. This was an important aspect to consider in the analysis since the clustering algorithm used is based on undirected graphs. The weight from the edge connecting nodes A and B is based on an average calculated from the samples between countries A and B, i.e. the average of A→B and B→A measurements. This means that if A → B and B→A delays are too different (too asymmetric), then their averages would be very unrepresentative. For this reason, the dataset had to be cleaned by setting aside the highly asymmetrical pairs. Up to 5% of the dataset had an asymmetry greater than 100 ms. Figure 7.5 depicts the distribution of RTT differences and shows how the RTT differences decrease linearly up to the 100 ms, beyond which there is no clear pattern.

Based on the latency dataset on its own, some general conclusions could be reached. First of all, in-country measurements were noticeably lower than those between different countries. Secondly, all results originating from country A and targeting the rest of the countries, were not necessarily similar to those originated from the rest of the countries and targeting country A. As mentioned above, this asymmetry in the dataset was properly handled in those cases which the country pair showed too much asymmetry. Third and last, some countries exhibited either “very good” or “very bad” connectivity to the whole region, when compared to the rest of the countries. Examples of countries with good general connectivity include Tunisia and Morocco, and to some extent Madagascar and Mauritius (Indian Ocean islands)

[3]RIPE Routing Information Service, last accessed on 2021-04-12, https://ris.ripe.net/

showed higher latency values. Noticeably, South Africa did not seem to be a leader in terms in general connectivity to the rest of Africa.

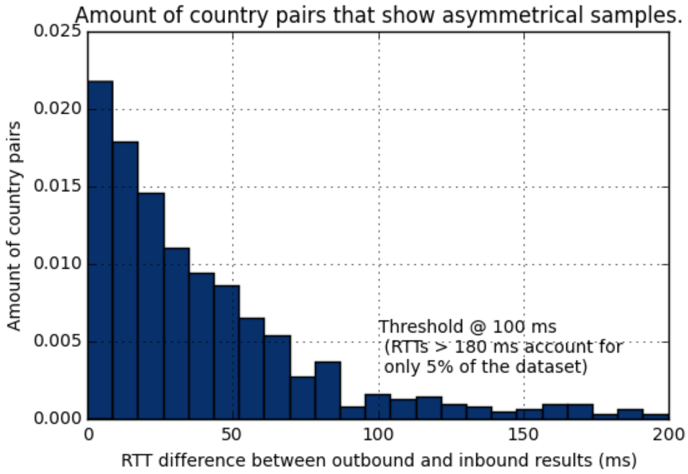


Figure 7.5: Distribution of countries pairs that show asymmetrical samples. The data suggested a threshold at 100 ms, where the symmetrical tendency was broken and marked the beginning of a long random tail

7.2.4 Limitations

It is important to highlight the limitations of the data collected in this study. First, there was limited insight into the devices launching the measurements, *e.g.,* their network access technology. This means it is difficult to provide causal insight into the performance of *individual* measurement samples. That said, the study yielded a sufficiently large number of samples from each country to extract regional trends. Second, all measurements were launched against Speedtest servers. Although they have a wide geographical distribution, they are not necessarily representative of future server deployments. Hence, future services may observe different performances based on how and where they deploy their servers. Third, due to the nature of the Speedchecker service, it was not possible to launch all pings and traceroutes in parallel from the same locations. Hence, different locations across the period of the campaign were sampled. Due to this, data aggregation was performed to underpin the clustering and analysis. Although not ideal, this allowed more tractable exploration and provided some insight for "typical" users. Finally, the study also highlighted known limitations with geolocation databases — it is very likely that discrepancies within MaxMind introduced noise to the data. However, as stated above, the study only performed a country-level analysis [132] (to minimise impact). On a side note, this limitation is applicable to any study reliant on geolocation.

7.3 Clustering Communities of Connectivity

One of the goals of this research was to detect the strengths and weaknesses of the connectivity in the African Internet. As a precursor to this, the relationships between countries by clustering them based on their latencies, were analysed.

7.3.1 Clustering methodology

First, the latency measurements were converted into a graph structure (G) that represented connectivity between countries. Each node in the graph was a country, whilst a link represented a set of latency measurements between two countries. The links were weighted by the *median* latency observed.

Second, the median value was selected as it provided insight into the "typical" delay seen between two countries, although clearly this removed a portion of data — particularly outlier networks within a country. In some cases, there were significant variances and outliers in the dataset, resulting in a skewed data distribution. The variances in latency measurements could be due to diurnal effects of congestion and path variabilities. To address the impact of outliers in the analysis, the median was used to represent the delay between countries.

Once the weighted undirected graph G is computed, countries were cluster based on their latency-defined distance using the Louvain algorithm [171]. The Louvain community detection algorithm is based on the modularity function, which performs clustering based on the measure of partition between communities found in a network. Let $G = (V, E)$ be the graph of vertices V representing countries and E, a set of undirected edges representing latencies. Suppose $u, v \in V$, $e(u, v) \in E$ has a weight w_u, v, which is the median latencies from $u \rightarrow v$ and $v \rightarrow u$. The community detection algorithm partitions the graph into communities, C, as expressed by Equations 7.1 and 7.2. This is very similar to the problem identified by Newman *et al.* in [172].

$$\cup\, c_i = V, \forall c_i \in C \tag{7.1}$$

$$c_i \cap c_j = \emptyset, \forall c_i, c_j \in C \tag{7.2}$$

The quality of the partitioning was measured using *modularity* Q [173], where $-1 < Q < 1$. The *modularity* was defined as the difference between the number of intra-cluster communities and the expected number of edges. Executing the algorithm output the set of strongly connected communities. It is expressed as follows:

$$Q = \sum_{c \in C} \left[\frac{\sum_{in}^{c}}{2m} - \frac{(\sum_{tot}^{c})^2}{4m^2} \right] \tag{7.3}$$

where $\sum_{in}^{c}$ is the sum of all weights (latencies) of all internal edges of a community c and $\sum_{tot}^{c}$ is the sum of weights (latencies) from edges incident to any vertex in community c. m $= \sum_{e(u,v) \in E} w_{u,v}$ is used to normalise the modularity and is obtained by adding the latencies across the entire graph. Once it is known how to calculate *modularity*, the Louvain algorithm [174] is run to greedily maximise the modularity gain when moving a vertex u to community c.

The Louvain method works in two distinct phases, executed one after the other until convergence is reached. It first detects community within smaller communities by optimising modularity locally. It then uses the communities detected to aggregate them into bigger communities until a maximum of modularity is reached. The outcome is a hierarchy of communities. The higher the modularity the denser the connections are within a cluster and the less dense the connections are between nodes of different clusters.

Algorithm 1 Louvain Algorithm pseudocode

```
G the initial network
repeat
    Put each node of G in its own community
    while some nodes are moved do
        for each node n of G do
            place n in its neighbouring community
            including its own which maximises the modularity gain
        end for
    end while
    if the new modularity is higher than the initial then
        G = the network between communities of G
    else
        Terminate
    end if
until no more nodes
```

The Louvain Method was tested in multiple studies which confirmed the efficiency of the algorithm on large networks, especially in the study of Online Social Networks (OSNs) [175, 176, 177, 178, 179, 180, 181]. Though, without a necessarily large network from the dataset (due to the fact that the study mainly focused on Africa), the Louvain Method will be a good fit if this experiment expanded to incorporate other countries of the world. This study therefore provides a basis for future work at a larger scale.

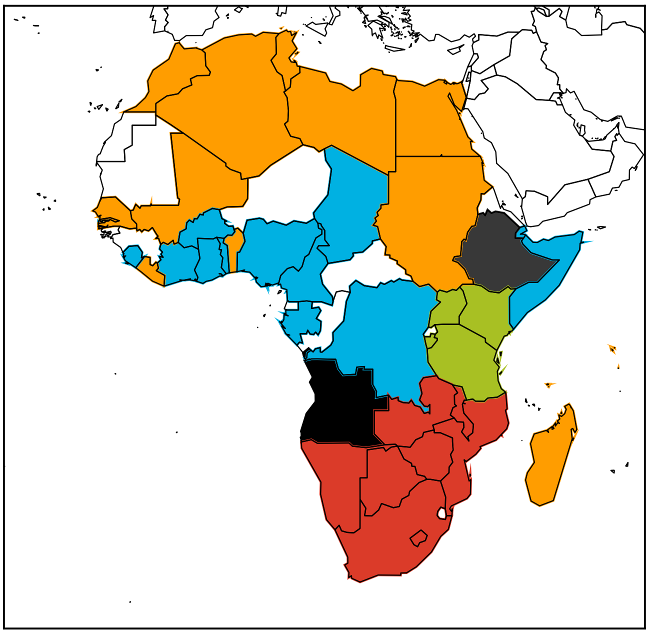


Figure 7.6: Country clusters according to the Louvain clustering algorithm. Yellow is Northern; Red is Southern; Blue is (mostly) Western; Green is Eastern. Ethiopia (grey north-east) and Angola (black south-west) showed no clear cluster membership.

7.3.2 Clustering results

The algorithm returned countries grouped into *four* different clusters, which corresponded to the regions of Northern, Southern, Eastern, and Western Africa. Figure 7.6 presents a map of the clusters with the summary of delay statistics for each cluster in table 7.1.

Unsurprisingly, the clusters follow clear geographical properties. However, there were a number of unusual trends: most noticeably, Guinea, Liberia and Benin on the West coast, with neighbouring countries from a different cluster. Similarly, Madagascar, Seychelles and the islands of the Indian Ocean, were clustered alongside countries in the North. Somalia, on the East coast, was clustered with countries on the West coast. This suggested that geography was not the sole factor in defining delay. This was explored in §7.4 and §7.5.

The clustering algorithm also returned two special cases: Angola and Ethiopia, which were placed in separate clusters on their own. To understand this, the study

Cluster name	Cluster colour	Intra-cluster median RTT	Intra-cluster Std	Inter-cluster median RTT	Inter-cluster Std
Northern	■	79	102	243	75
Southern	■	45	88	243	109
Eastern	■	28	120	205	122
Western	■	205	124	292	93

Table 7.1: Summary of delay statistics for each cluster

took a closer look at their latency profiles. Figure 7.7 depicts the distribution of RTTs between these countries and all other countries in the four clusters. It was also observed that Libya was an example of a country that showed typical (normal) trends. Libya exhibited very different delays across the different clusters. It had low delay to countries in the Northern cluster, but high delay to all others. In contrast, Angola and Ethiopia had roughly equivalent delays to countries within all clusters. For example, the median delay from Angola to all clusters was consistently above 200 ms. This explains why the algorithm could not allocate them to any clusters. To allocate them to an appropriate cluster, the data was manually inspected. The median delay from Angola ↔ Western cluster was 273 ms, which is 1.33x the median intra-cluster delay. The other options considered resulted in 8x, 2.7x, and 6.8x to the Eastern, Northern, and Southern clusters. Hence, Angola was allocated to the Western cluster. The same ratios were computed for Ethiopia, which was also allocated to the Western cluster. The study discusses the implications of this in §7.5. These results can be compared against Somalia, which was also allocated to the Western cluster (by the Louvain algorithm).

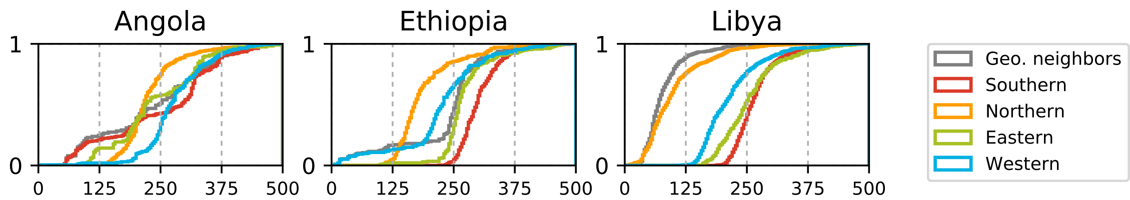


Figure 7.7: CDFs of RTTs (in ms) between the 4 clusters and some special cases: Angola and Ethiopia. Libya is added as a reference of a normal case. RTTs to each country's neighbours are also shown.

Following the same reasoning, Ethiopia showed a lower latency ratio against the sparse Western cluster: 1.1x the cluster's intra-cluster latency. Therefore, Ethiopia also became part of the Western cluster.

The case of Somalia is similar: Somalia was closer to the Northern (yellow) cluster in absolute latency values (79 ms), yet adding Somalia to the cluster means adding a low-performing node, with 1.21x the cluster latency. In this case, this was a direct result from the Louvain clustering algorithm, so it was decided to keep Somalia in the Western cluster.

7.4 Quantifying delay in Africa

Before exploring the topology of Africa, this research quantified the delay attained between its countries. Note that delay is often the most prominent bottleneck of various protocols and applications [182, 183].

7.4.1 Exploring inter-country delays

Figure 7.8 presents a heatmap of the inter-country median delays observed (where the country originating the measurement is displayed vertically on the left and the target country is displayed horizontally on top). As expected, the lowest delays can mostly be observed within *intra*-country delays.

There were also a number of inter-country delays that exhibit similarly low delay characteristics. These were primarily countries with close geographical proximity. For example, the delay between Tunisia and Algeria was just 48ms. This can be compared against the intra-country delays within these countries, which were 25ms and 44ms respectively. Examples of non-neighbouring countries with delays below 90ms included Kenya and Zimbabwe at 85ms, and Mauritius and Tanzania at 80ms.

To generalise this, Figure 7.9 presents a CDF of the inter and intra country delays. For context, the same data from the Latin America and the Caribbean (LAC) region were included using the same Speedchecker methodology (taken from [184]). Across the entire Africa dataset, *intra*-country latencies average at 78ms. This was significantly higher than that seen in more developed regions; the average monthly latency in North America is <45ms and <30ms for Europe [168]. The results were, however, close to the 76ms measured in the LAC region [184] (which is in a relatively similar state of Internet development).

However, the story was significantly different when comparing *inter*-country delays, also shown in Figure 7.9. Africa had a mean of 280ms, whilst the LAC region had only 154ms: a factor of 1.8x. 9% of inter-country delays exceed 400ms, and

2% exceed 500ms (shown in red). Again, this can be compared against the measurements performed in the LAC region, where less than 1% of country pairs have a latency greater than 500ms. In fact, these African delays were so poor that they went well beyond the sensitivity analysis ranges used by past studies that inspect the impact of network delay on things like web page load times [185] and video streaming performance [186]. For example, ranges of only 0–100ms were tested in [186]. In other words, past application performance studies would need to be entirely repeated with vastly higher delay parameters to understand their behaviour in Africa. This observation partly explained the reason why recent studies had found such little content infrastructure in Africa [89]: the delays incongruous with high performance. Considering the delays between countries in Africa, do not exceed those seen from Africa to Europe it therefore creates an incentive for European hosting which is typically cheaper [29].

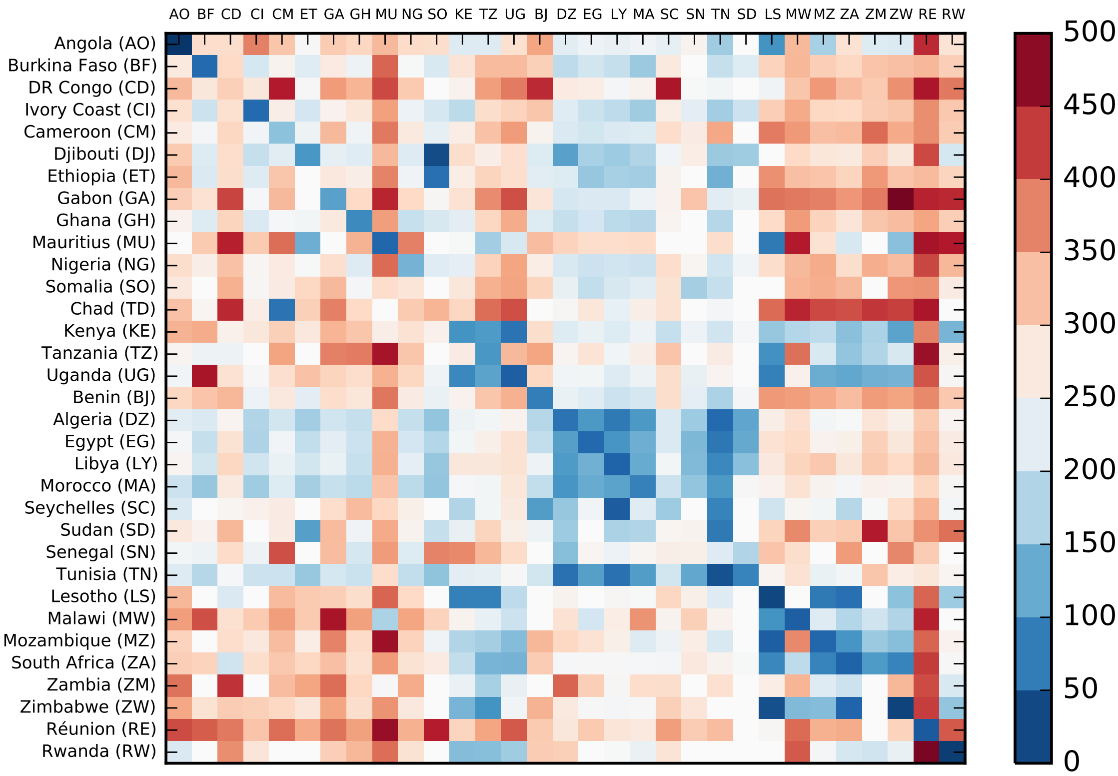


Figure 7.8: Country-level (median) latency heatmap. Countries are ordered by latency proximity. White colour indicates no meaningful samples could be gathered between that pair of countries. Countries excluded that had more than 20 white cells.

7.4.2 Exploring inter-cluster delays

The above presented the delays observed between individual countries. However, the findings in §7.3 had already identified that some groups of countries were better

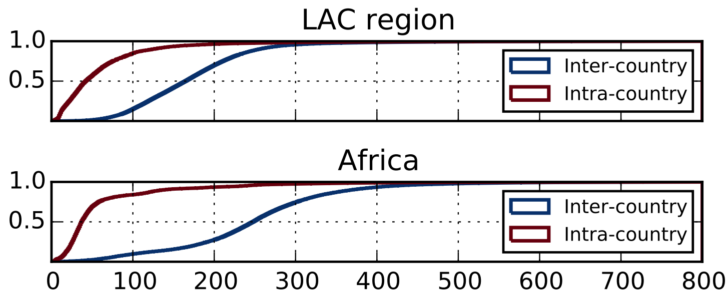


Figure 7.9: CDFs showing intra-country and inter-country RTTs for the LAC region (taken from [184]) and Africa

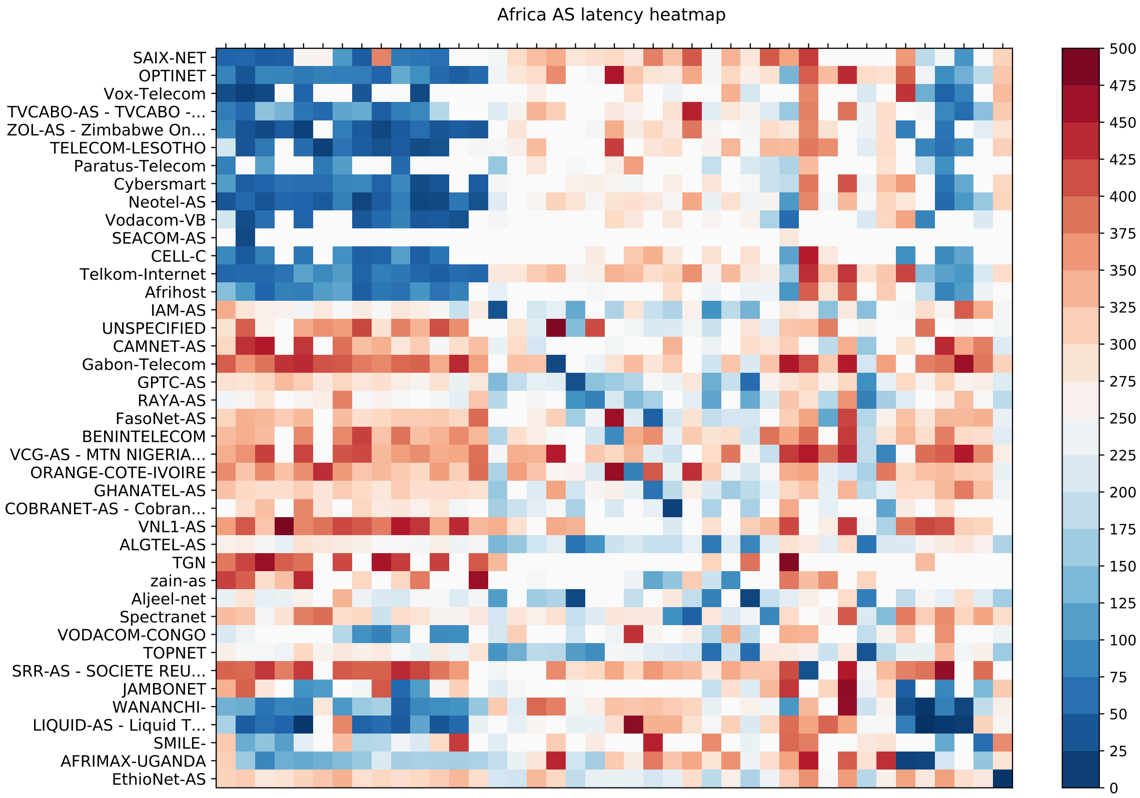
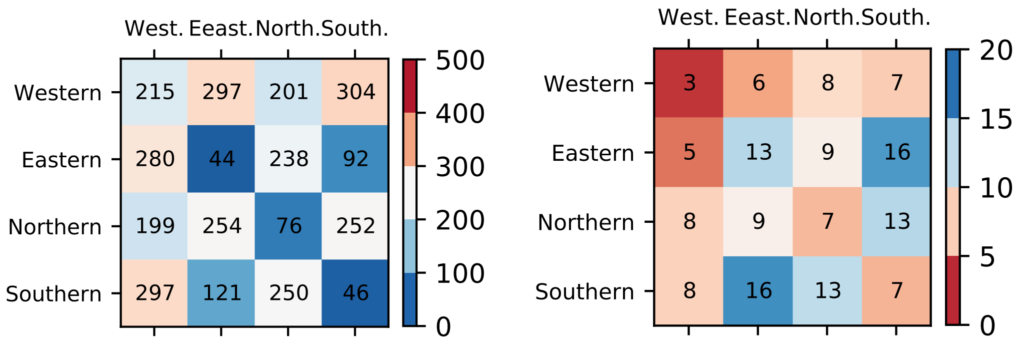


Figure 7.10: Partial view of the AS-level latency heatmap, aggregated by the mean. For practical purposes only 10% of sampled networks (41 out of 392) are displayed. ASes are ordered by latency proximity. White cells indicates no meaningful samples could be gathered between that pair of ASes. ASes excluded had more than 100 white cells.



(a) (b)

Figure 7.11: Heatmap (a) shows median RTT, aggregated at cluster level. Heatmap (b) shows delay normalised by distance (based on equation 7.4).

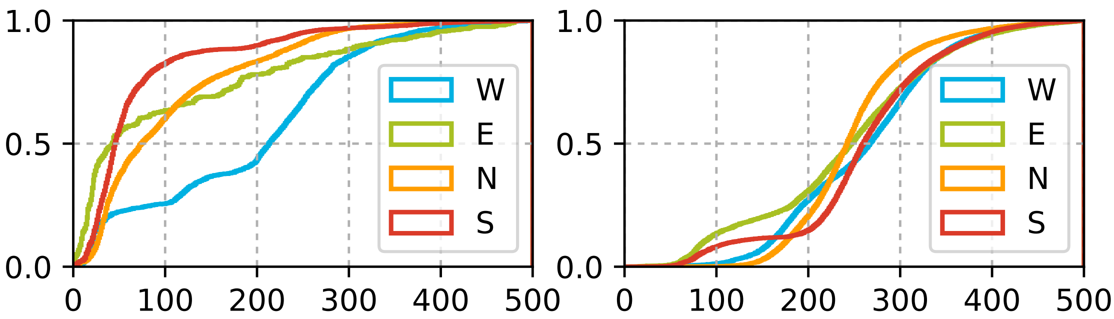


Figure 7.12: CDFs showing intra-cluster RTTs (left) and inter-cluster RTTs (right)

interconnected than others. Hence, this study next inspected the delays observed between the clusters from §7.3.

Figure 7.12 presents the CDFs of all delay samples split into clusters. It can be seen that, although there as a significant amount of overlap between the clusters, the Western cluster performed worse on an intra-cluster basis. The Southern cluster had the lowest delay. In contrast, the inter-cluster delays were consistently worse across all clusters, with over half of all samples exceeding 200ms. To complement the CDF, Figure 7.11a shows a heatmap of the median delays seen *between* clusters. Again, it can obviously be seen that intra-cluster delays were generally lowest. For example, the Eastern cluster had the lowest intra-delay (median of 44ms), which placed it in a similar position to Europe. The one outlier was the Western cluster, which had a high median delay of 215ms. In terms of inter-cluster delays, the Southern and Eastern clusters had the lowest delay between them (median of 92ms).

There was, however, a key limitation in the above analysis. Small countries in close proximity would naturally have lower propagation delays (assuming direct links). Thus, in some cases, low RTT may simply be a property of geography. To address this, the delays were normalised based on the geodesic path between the source and destination; this captured the *delay stretch*. The stretch was computed, for each ping sample, p, as:

$$stretch^p = \frac{d/(RTT^p)}{c \times 0.66} \tag{7.4}$$

where d is distance to the destination and c is the speed of light. c was reduced by a factor of 2/3 to approximate propagation time through optical fibre [187]. RTT^p was taken as the minimal RTT (in seconds) measured from a given ping sample, p. The stretch therefore captured the ratio between the optimal observed RTT and the theoretical minimum RTT. It is assumed there is no overhead, noise and packet loss during the ping test.

Figure 7.11b shows a heatmap containing the stretch value between each cluster. High values indicate strong connectivity; for example, a value of 20 indicates that the speed of the packet is 20% of the maximum theoretical speed. By comparing figures 7.11a and 7.11b, this helped to identify differences. In figure 7.11b, some *inter*-cluster delays were actually lower than *intra*-cluster delays when measured using this normalised metric. In other words, some low observed RTTs were a property of geography — the clusters were still highly suboptimal. A good example was the Southern ↔ Eastern cluster, which had a high median delay of 92ms, yet performed far better when normalised by distance. Whereas Southern ↔ Southern only attained 7% of the optimal speed (46ms), Southern ↔ Eastern gained 16%.

That said, there are some results that were consistent between the two heatmaps, namely the poor performance of the Western cluster. To explore why this might be, the study initially checked Somalia, as it was actually geographically located on the Eastern coast (*cf.* Figure 7.6). However, curiously, Somalia actually had the fastest intra-cluster ping measurements in the Western cluster: located at around 20% of $0.66c$. The ping speeds in the remaining countries, instead, attained around just 5% of $0.66c$.

7.5 Dissecting Paths Across Africa

The previous section highlighted the high network delays suffered when traversing countries in Africa. Next this research inspected the reasons behind this using the topology maps obtained via the traceroute campaign.

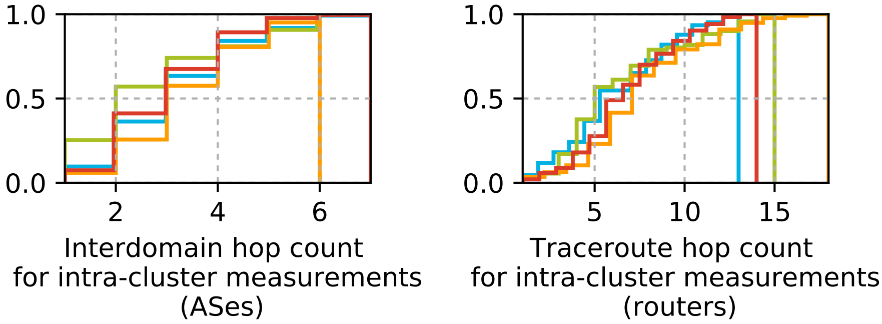


Figure 7.13: Number of AS and router-level hops traversed by the traceroute

7.5.1 Exploring topological traits

To begin, Figure 7.13 presents the distribution of hop counts across all traceroutes within the same clusters (*i.e.,* where the Speedchecker client and Speedtest server are in the same cluster). It can be seen that the traceroutes originating from the Eastern cluster had marginally fewer hops than the others (median 5 router hops). Curiously, however, the Western cluster (which was the worst performing) also had fewer AS (median 3) and router-level (median 6) hops than the Northern and Southern clusters. This suggests that the higher delays were *not* simply driven by hop counts. Figure 7.14 presents a geographical map showing the upstream providers[4] serving all networks sampled in each country. This offered immediate insight into the reasons behind the high delays previous seen. It was found that a significant number of networks rely on upstream providers outside of the continent. Considering all traceroutes, it was observed that 37.8% of all routers in the data are geolocated outside of Africa. The remainder inside Africa were heavily biased towards a few prominent countries, namely South Africa and Mauritius via the West Indian Ocean Cable Company (WIOCC). 6.6% and 4.5% of traces upstream through them, respectively. Hence, although the hop counts did not differ significantly, the locations of the networks did. From the 207 networks sampled, the study found that 37.8% utilised upstream providers outside of Africa. The remainder inside Africa were heavily biased towards a few prominent countries, namely South Africa and Mauritius via the West Indian Ocean Cable Company (WIOCC). 6.6% and 4.5% of networks upstream through them, respectively.

Figure 7.15 presents the most popular countries for hosting upstream networks. It can be seen that South Africa offered the most upstream provision, followed by

[4]upstream is defined as the first AS hop after the origin AS hosting the Speedchecker client.

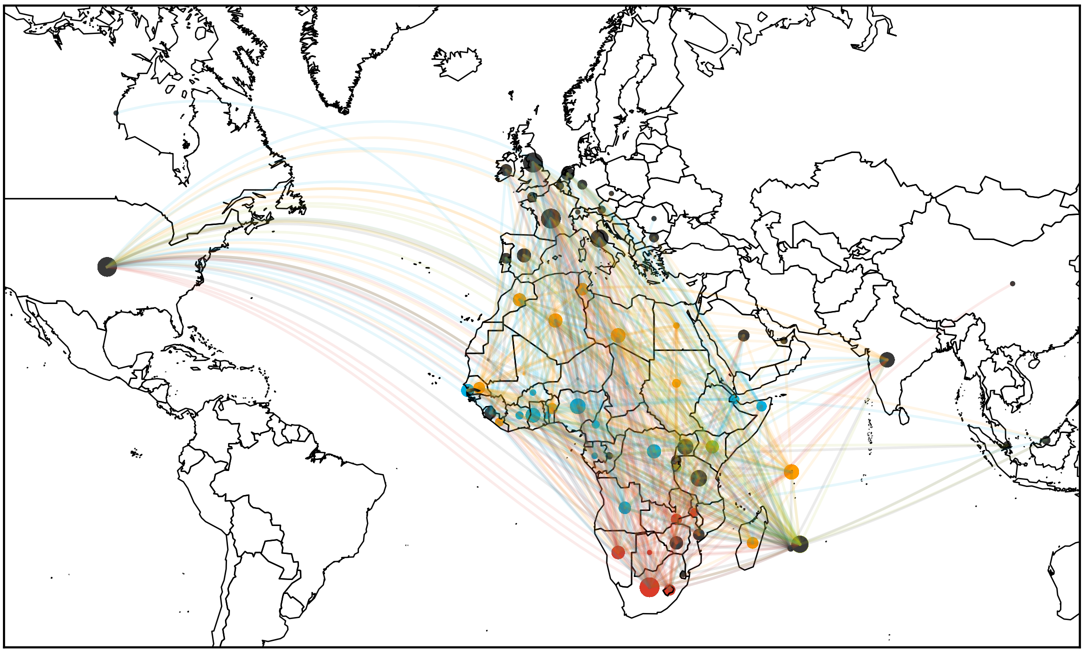


Figure 7.14: Map showing the first AS hop in the traceroute dataset. Countries with multiple networks had multiple links shown. Nodes colours correspond with their cluster's colour, node sizes correspond with their in-degree.

the UK and US. Interestingly, the use of the these upstreams differed substantially based on cluster, with regional hubs emerging, *e.g.,* Uganda for the Eastern cluster and South Africa for the Southern cluster.

Next, the specific upstream networks involved in these AS hops were inspected. Table 7.2 presents a list of the top upstream providers ranked by the number of edge networks connected to them by their first AS hop. The Top 10, alone, provide services to nearly half of all sampled networks. Rather than observing local tier-2 operators, the list was dominated by international tier-1 operators. Anecdotally, many African network operators preferred to use such services due to their perceived reliability and international reputation. Table 7.3 offers an alternative perspective, ranking the networks by highest degree centrality. WIOCC, Econet Telecom and PCCW were added to the ranking. It was also worth briefly noting that there was a significant presence of the French operator, Orange. 17% of networks in French-speaking countries utilised Orange, which added up to almost 40% of Orange's downstreams (potentially driven by historical ties) whilst a majority of networks in English speaking countries utilised upstream providers who were domiciled in English speaking regions.

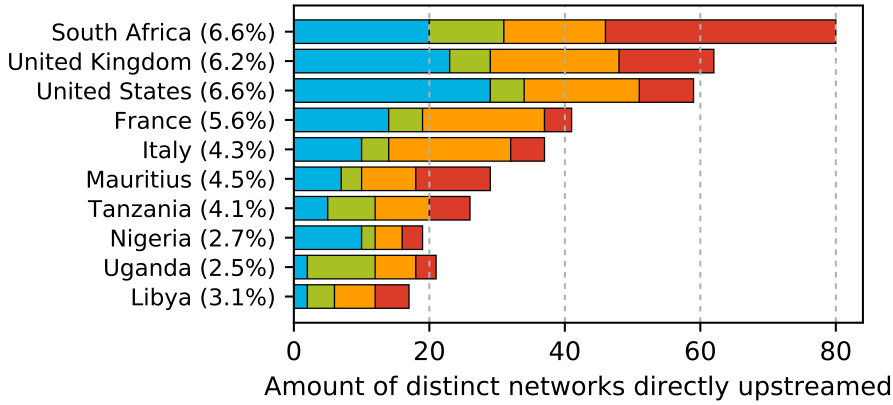


Figure 7.15: Number of networks upstreaming through each country. Network samples separated into their clusters.

The above showed that many countries relied on international and intercontinental upstream providers and explained the propensity for countries in the Western cluster to suffer from such high inter-country delays: a significant fraction of paths were circuitous and left the continent before re-entering the destination country. An obvious follow-up was what *proportion* of paths from each country follow these intercontinental routes. To answer this, the study inspected the hops taken through each AS on a per-sample basis. Figure 7.16 shows the percentage of traceroute hops that traverse each region. For each traceroute, the sequence of distinct ASes (that the traceroute went through) were explored. Each stage in the figure indicates the AS path traversed so far. The first column corresponds with 0 hop count (origin), the second one with the first hop count, *etc.* The first observation was that a large fraction of traceroutes had their first hop in an overseas region (50%), in particular through Europe. The results showed that Europe acted as a major Internet provider to networks across Africa (35%), and to the Northern cluster in particular (transiting ≈40% of the cluster's traceroutes). Considering the geographic distance, it was surprising that 12% of African connections were routed through N. America. Arabia and Asia only account for 3% of outgoing paths. This also disproved the theory that only Northern African countries rely on Europe and Arabia.

Figure 7.16 further shows that intercontinental hops are not limited to the immediate (first hop) upstream provider. It was found that even edge ASes that utilised African upstream providers saw their traffic leaving the continent (potentially without their prior knowledge). This was because their upstream providers, in turn, utilised international transit rather than local peering. For example, 14% of traceroutes went via overseas parties for as many as 4 interdomain hops before returning to African operators. A particular case of this phenomena was the traffic exchange between N. America and Europe: 3.5% of the traceroute paths were routed between these two locations, even though all source and destination locations were within Africa. Naturally, this becomes a challenging problem to address as it is outside of the control of African edge networks, which largely depend on the routing decisions made by their upstream operator.

In order to have a better grasp of this situation, where African operators' traffic takes unintended suboptimal routes (in a second, third, or subsequent interdomain hop), an AS-level graph was built based on the traceroute data and calculated the top 10 most *central* networks. This calculation was based on the degree centrality of each node (AS). The results can be better seen in Table 7.3. Table 7.3 extended Table 7.2 by considering the full chain of AS hops, instead of just the first one. Table 7.4 performed the same analysis, based on a country-level graph.

As mentioned earlier, the study launched a parallel traceroute campaign in order to complement the ping dataset. By crossing the ping and traceroute datasets it could be inferred that large ping times were correlated mostly with high hop count; in general terms a linear tendency was respected, besides some cases related mainly with the Central cluster, which can be better seen in Figure 7.17. Those cases showed a low hop-count but a large RTT, which hinted that the cause was other than poor routing. This strong correlation proved empirically that suboptimal packet routing was most likely the main cause behind large ping times in the continent.

Rank	**ASN**	**Network info.**	**Perc.**	**Centrality**
1	174	Cogent Communications	10.3%	0.095
2	3356	Level 3 Communications	7.4%	0.087
3	37100	SEACOM	7.1%	0.065
4	6762	Sparkle (TIM Group)	6.6%	0.071
5	30844	Liquid Telecom	5.9%	0.137
6	5511	France Telecom (Orange)	3.9%	0.044
7	57023	Oranlink	2.3%	0.003
8	6453	TATA COMMS. - US	2.2%	0.013
9	16637	MTN	2.1%	0.029
10	5713	Telkom SA Ltd	2.0%	0.019
Sum			49.7%	

Table 7.2: Top 10 networks providing direct upstream access to African networks (first AS hop considered). Percentage is based on the fraction of traceroutes the ASN appears as a direct upstream.

Ranking	ASN	Network info.	Centrality (normed)
1	30844	Liquid Telecom	0.296
2	174	Cogent Communications	0.257
3	3356	Level 3 Communications, Inc.	0.254
4	37662	WIOCC	0.222
5	3491	PCCW Global, Inc.	0.216
6	6762	Sparkle (TIM Group)	0.207
7	37100	SEACOM	0.192
8	8881	Versatel	0.189
9	33567	Econet Telecom Lesotho (PTY)	0.183
10	5511	France Telecom (Orange)	0.148
Top 10			2.165

Table 7.3: Top 10 networks providing access to African networks (all AS hops considered). Centrality is based on each network's *degree of centrality*.

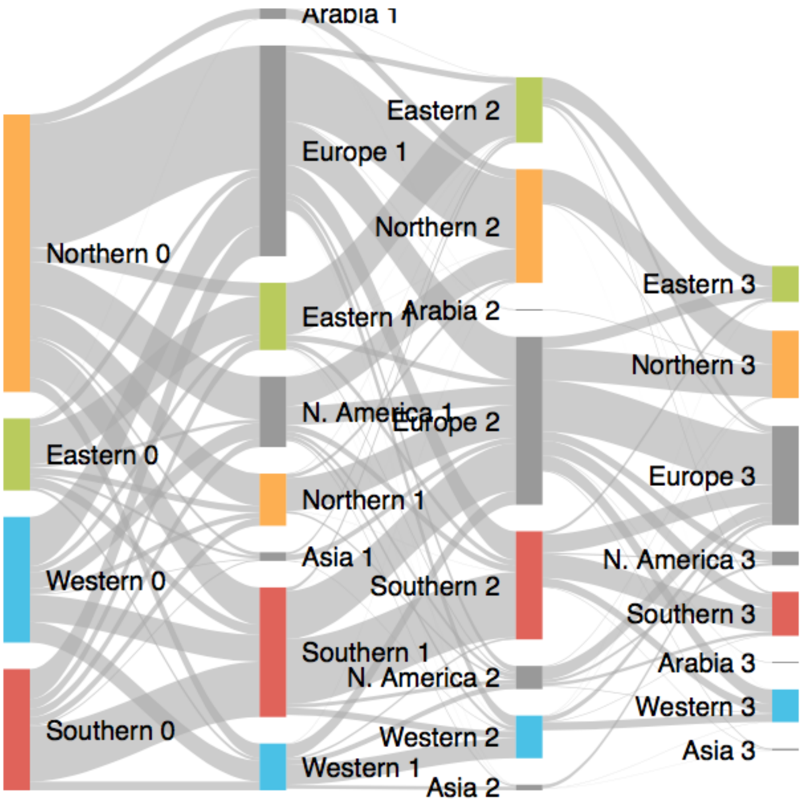


Figure 7.16: Hop-by-hop analysis of traceroute data. Each step indicates the fraction of routers that fall into each cluster along the traceroute hops.

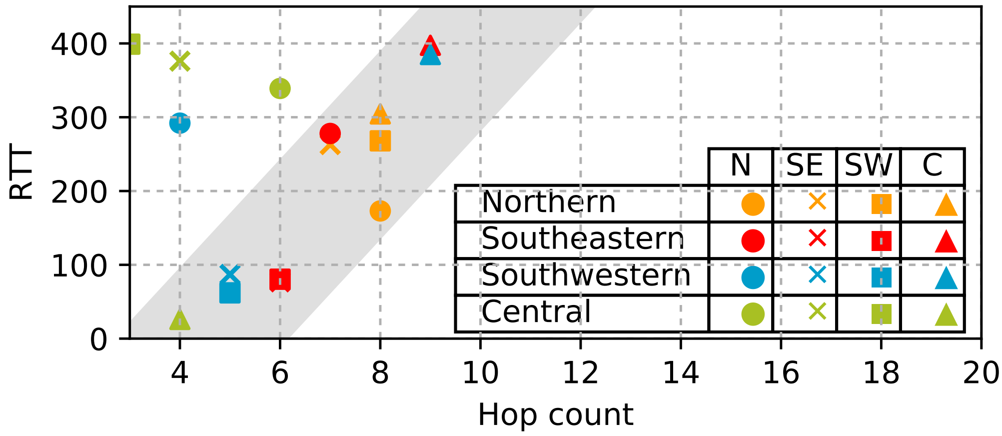


Figure 7.17: Scatter plot between traceroute hop count and ping RTT. Countries originating the ping and the traceroute are displayed on the left of the table, and countries being target of the ping and the traceroute are displayed on top. A general linear tendency was respected, besides the results involving the Central/Eastern cluster (green cluster see Figure 7.6). Sidenote: Red X and red square are overlapped.

7.5.2 What are the delay implications?

The above showed that a large number of operators choose to utilise upstream providers outside of their own country (or even continent). To explore the implications of this, Figure 7.20 presents the minimum delay from African ASes to their upstream providers, *i.e.,* the minimum RTT to the first hop outside the edge AS. The minimum was used to capture the best possible scenario. The results revealed the performance *cost* of choosing to use intercontinental upstream provision.

Ranking	**Country**	**Centrality (normed)**
1	United Kingdom	1.07
2	United States	1.00
3	France	0.92
4	South Africa	0.89
5	Mauritius	0.78
6	Italy	0.66
7	Kenya	0.58
8	Egypt	0.50
9	Angola	0.50
10	Tanzania	0.50
Top 10		7.39

Table 7.4: Top 10 countries providing access to African networks (all AS hops considered)

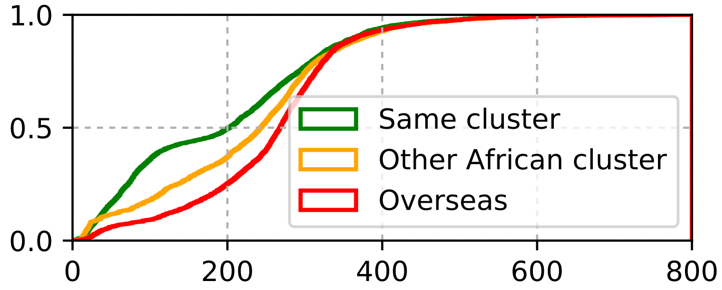


Figure 7.18: CDF of all RTTs from samples classified into three categories based on the first-AS hop upstream provider used by the origin network

It can be seen that networks using upstream providers within their own cluster gained the best first-hop delay (median 40ms). Curiously, the Western cluster was amongst the best performing when using this metric. Note, however, that the use of a local upstream provider did not guarantee high end-to-end performance. For example, in the Western cluster, 3.15% of traceroutes exiting the cluster were still intercontinental despite the use of a local first-hop upstream.

As a consequence of this, it can also be seen that regions that utilise intercontinental upstream providers had much higher delays. For instance, Southern networks that used Southern upstream providers witnessed a minimum of 47ms delay; this can be compared against 227ms when using N. American providers. Strangely, though, intercontinental delays were lower than some inter-cluster delays. Southern networks that used upstream providers in the Northern cluster saw a minimum delay of 299ms. In fact, on average, clusters were marginally closer to overseas upstreams than to upstreams in other African clusters (180 vs. 195ms). That said, *intra*-cluster upstream consistently outperformed both of these scenarios.

The overall impact these decisions have across the entire set of latency measurements was also investigated. For this, *all* ping samples were split into (*i*) networks that used an up-stream provider within the same cluster; (*ii*) networks that used an African upstream in another cluster; (*iii*) networks that used an overseas provider for over 50% of traceroutes observed. Figure 7.18 presents CDFs of RTTs seen within each group. It can be seen that, indeed, the lowest delay networks were those that upstream through a network within their own cluster (203 ms median). In line with earlier discussions, the delta between networks using international providers and those based in other African clusters was limited (268 *vs.* 243 ms median).

Figure 7.19 presents the relationship between the number of upstream links outside Africa, and the relationship between intra cluster RTT. The hypothesis was that

Upstream GeoLocation / RTT	1st Q	Mean	3rd Q
NorthAfrica	30	101	138
SouthEast	15	72	85
SouthCentral	12	87	185
Intercontinental	77	152	202

Table 7.5: RTTs to upstream providers grouped by geolocation

clusters with high delay were more likely to upstream via distant networks (because their local ecosystem was not well developed).

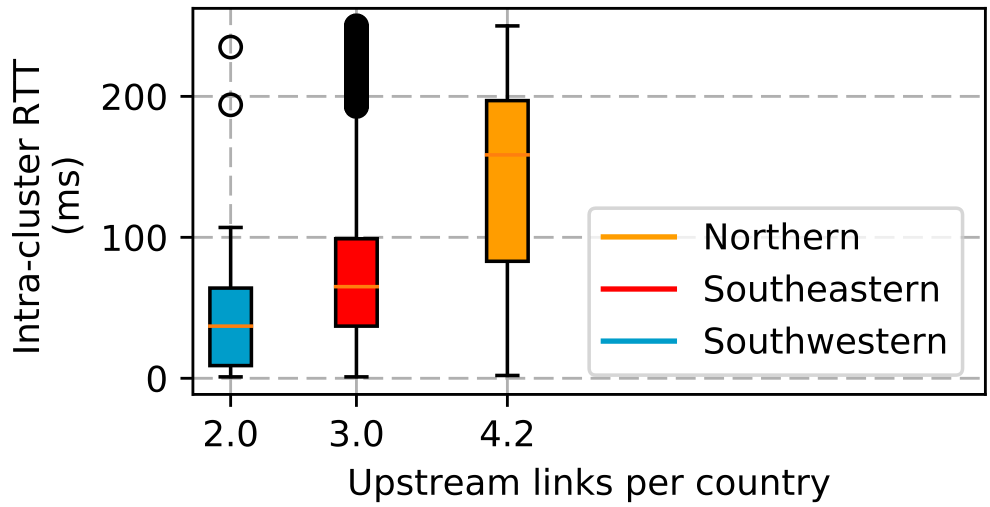


Figure 7.19: Relationship between amount of upstream links outside Africa and Intra-cluster RTT, aggregated by cluster; the greater the amount of overseas upstreams, the greater the RTT. Colours correspond with those in Figure 7.6

.

7.5.3 Addressing the delay bottlenecks

To take an initial step towards evaluating the potential delay enhancements of networks using local interconnection, this study briefly experimented with alternative upstream configurations. Specifically, for intra-cluster latencies, the overseas upstream hops were replaced from all paths by the median intra-cluster hop. Implementing such a policy would result in significant enhancements, with an 81% improvement for networks in the Eastern cluster (21ms to 4ms), as well as 45% (60ms to 33ms) and 72% (47ms to 13ms) for the Northern and Southern clusters respectively.

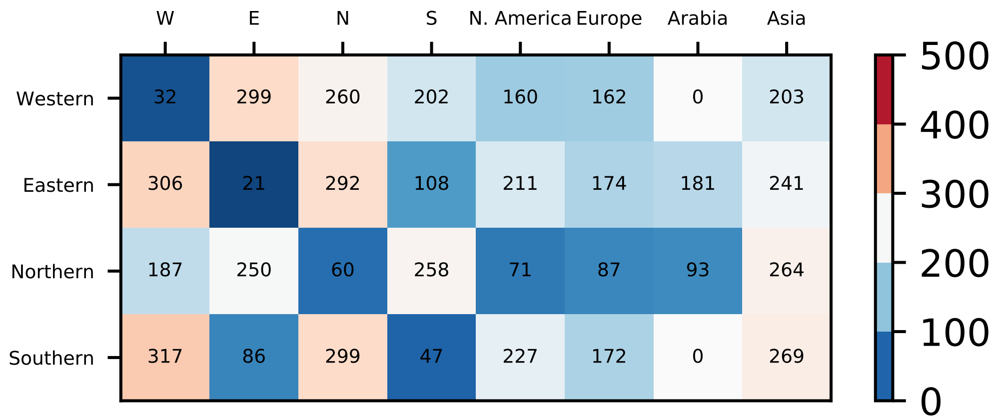


Figure 7.20: Heatmap showing min. RTT to the first AS outside the origin AS network. This heatmap differs from the one in Figure 7.11a by showing min. RTT to the first AS.

Cluster	**W**	**E**	**N**	**S**
Western	direct	WWWSEE	WWWSEEN	WWWS
Eastern	EEESWW	direct	EEEEN	EEES
Northern	NEur.WW	NNEEE	direct	NNEES
Southern	SSWW	SSEE	SSEEN	direct

Table 7.6: Clusters hops suggested by the shortest path algorithm. Note how overseas hops were almost completely avoided

When broadening the scope of these imaginary conditions by taking them outside same-cluster scenarios, and considering not just the first AS hop but all AS hops in the traceroute data, what routing suggestions can be given to have a better regional connectivity? Based on the traceroute dataset, and assuming there was a pretty general symmetry at a cluster level, an undirected graph was built, having clusters as nodes and RTT as edges, and computed a weighted shortest path between the clusters. Considering the good intra-cluster latencies and the bad inter-cluster latencies, it was not surprising that solutions for intra-cluster paths remained the same as before. However, results for inter-cluster shortest-paths showed that a) they avoided overseas hops entirely and b) the use of good intra-cluster was maximized by developing chains of intra-cluster hops, and cluster changes were performed only when needed.

Cluster	W	E	N	S
Western	none	69%	59%	71%
Eastern	66%	none	76%	65%
Northern	33%	60%	none	67%
Southern	71%	10%	76%	none

Table 7.7: Improvements from performing local routing instead of circuitous routing through overseas upstreams

7.5.4 Revisiting Angola and Ethiopia

It was already highlighted the problems with allocating Angola and Ethiopia to clusters (§7.3). This motivated this study to further explore the topological reasons that caused the result. Note these were allocated to the Western cluster which consistently had performed the worst. To explain these results, the study started by inspecting the upstream provision. Angola and Ethiopia had very different upstreams selections: Ethiopia upstreams entirely through overseas providers, whilst Angola did it for 34% of the paths observed. In the case of Ethiopia, paths go through Europe (70%) and North America (30%). Considering the latency penalty of long haul links (Ethiopia → Europe at 354 ms, and Ethiopia → North America at 144 ms), the high RTT values were primarily driven by these circuitous routes. In contrast, Angola used African upstream providers in 66% of traceroute samples. This made it a more interesting case as, theoretically, it should therefore avoid connectivity through long haul links. However, when including the second AS hop, it was found that an additional 16% of traceroutes went through the Southern cluster and are subsequently routed through Europe, adding to a total of 50% overseas paths (routed either direct or indirectly). In other words, despite networks in Angola not *directly* using international transit, their upstream providers did so. When combined, this distorts delays from both Ethiopia and Angola and pushes them away from the centre on any of the existing clusters, explaining the observations made in §7.3.

These patterns also explained the poor delay performance exhibited by the Western cluster in general. For example, whereas the median intra-cluster delay of the Southern cluster was 46ms, it was 215 for the Western. When looking into the topology of the Western cluster, it was further noticed that just 38% of hops occurred between ASes within the cluster. Those intra-cluster hops benefited from shorter distances and have a median delay of 24 ms. The rest of hops were mostly Western → Europe hops (9.4%) which account for an added 132 ms (each way), and Europe

$\leftrightarrow$ Europe (21%), with marginal penalties. Thus, whereas other regions had built up strong intra-cluster connectivity, the Western region still lacked this.

7.6 Conclusion

This study on latency measurement in Africa showed that many countries within the same cluster share very much the same network characteristics. The Eastern and Southern blocks enjoyed the lowest in-country latency while the Northern and Central blocks enjoyed much higher latencies. It is well-known that Southern and Eastern African countries are very well connected both physically and logically. The Afterfibre[5] submarine and terrestrial cable map gives a good indication of cable density in this region. While it was sometimes difficult to infer, without further analysis, any directly relationship between latency and cable availability, it can be argued that the higher the cable density the lower will the latency be in the specific region, if the ISPs were interconnected. Indeed, availability of physical infrastructure is not enough to ensure low latency. This is where the interconnection between ISPs, either for transit (provider-customer relationship) or peering, plays a determinant role in keeping local traffic local. Further analysis would be required to correlate both physical and logical topologies with latency. South Africa, the largest regional hub, did not stand out in terms of latency to the rest of the region. After performing the clustering analysis it was found out that South Africa actually belonged to the cluster that was best connected within itself, but most distant from the rest of Africa: the Southeastern cluster. On the other hand, countries such as Tunisia had shown to have consistently good connectivity toward the whole continent.

On the other hand, Madagascar and Mauritius (two Indian Ocean islands) seemed to be one of the most low performing countries on the latency map. The reason could be the choice of upstream providers. It is common knowledge that many countries in Africa still preferred buying transit with European transit providers rather than on those operating on the African continent. Also, ISPs in Mauritius and Madagascar did not have peering agreement on the continent, data were bound to take circuitous routes for African destinations. Furthermore, it was interesting to see how Arabic countries have a relatively low latency between themselves. Actually, a short analysis over submarine cable topology in Africa, provided some basic but promising data such as degree for each node and shortest path between any two pair of nodes.

[5] Africa Terrestrial Fibre map, last accessed on 2021-02-12, https://afterfibre.nsrc.org

From the submarine cable infrastructure dataset it was inferred that South Africa acted as a major regional hub. Analogous way to aeroplanes' regional hubs, this also meant that in one or two hops the data can travel from end to end of the continent. For this case, zero hop means direct physical connectivity, one hop means having to go through another country before reaching its final country, etc. For Africa, the maximum amount of hops was two, so relationships between countries can traverse a maximum of three submarine links. This raised the important question of how physical topology influenced delay in end-to-end connectivity and cross-border communication.

Chapter 8

Democratising Access to Local Content Through Localised Internet Infrastructures

This chapter introduces a conceptual framework that rates the "readiness" of a country's data infrastructures to provide localised Internet services. The framework looks at the entirety of the content delivery value chain[1]. It takes into account indicators such as the availability and the efficiency of the local IXP, the presence of colocation data centres, CDNs, cloud providers as well as the regulatory framework that supports and promotes data storage and content hosting close to the end-users. Secondly, with indicators collected from the Internet Inclusiveness Index[2] and the PCH IXP directory, this study established the relationship between the size of IXPs and local Internet activity. For this, the research looked into regional indicators such as the number of domains under a Country-code Top-Level Domain (ccTLD) and the number of web pages indexed by Google for a ccTLD. Finally, keys policy recommendations were provided on how to improve the facilities to foster a conducive environment for local content hosting.

8.1 Introduction

In the past few years, there has been a quite disruptive change of the Internet architecture from a hierarchical multi-tier model to a more flatter one characterised by increased arrangements between network operators [188]. This change has been

[1]The content delivery value chain refers to the different interactions and stages involved in moving content from the content provider to the consumer.

[2]Economist Intelligence Unit, Internet Inclusiveness Index 2020, available at: https://theinclusiveinternet.eiu.com/ (accessed on 23 January 2021)

mostly driven by the need of network operators to respond to increasing demand in Internet traffic, by moving content closer to the edge and also reduce operating costs to remain competitive. At the same time, thanks to evolving policy frameworks and a more conducive market structure, more and more cooperative arrangements could be observed from local players e.g., eyeball networks. Eyeball networks are networks were most of the end-users are connected (as opposed to transit networks).

An enhanced national data infrastructure is therefore made up of important building blocks: an Internet Exchange Point (IXP) to keep local traffic local, Content Delivery Networks (CDNs) to increase proximity with the eyeball networks and facilities such as Data Centres (DCs) or cloud services that would foster content hosting within the national boundaries. The latter will help reduce the expensive usage of international bandwidth and consequently improve the QoE of end-users. In addition to the above, the ecosystem should be supported by a proper regulatory framework which must include data privacy law, domestic and cross-border data transfer policies.

Unfortunately, not all countries are at the same level playing field in terms of development of their national data infrastructure. Europe and North American are well-advanced than the rest of the world with as close as 500 IXPs, 15 times more than in Middle East and North Africa (MENA) region[3]. Figure 8.1 shows the countries in Africa, where an IXP is present. With regards to content hosting facilities, similar trends are observed. The ratio of colocation DCs between North America and sub-Saharan Africa is 1 to 20. In the US only, there are almost 1,500 DCs and cloud providers[4] serving around 400 million inhabitants. In sub-Saharan Africa, there are 75 listed DCs for a population of 1.1 billion.

It is without any doubt that an enabling and competitive environment has a positive impact on reducing costs to access content. Costs can be both financial and performance-related. For example, as per the 2019 A4AI Affordability report[189], the price of a 1GB bundle on average in sub-Saharan Africa is 6.8% of the monthly income, while globally it is less than 3% on average. The high cost of Internet access therefore does not promote growth of the digital economy and this naturally cascades into fewer investments in core infrastructure such as backbone fibre, cell towers, DCs, resulting in an overall poor national data infrastructure ecosystem.

It is a fact that the growth of the digital business ecosystem depends heavily on the demand-side. Actually, it has been observed in many countries that as the

[3]Packet Clearing House IXP directory, last accessed on 2021-04-29, https://www.pch.net/ixp/dir

[4]Data Centre Map, last accessed on 2021-02-12, https://www.datacentermap.com/

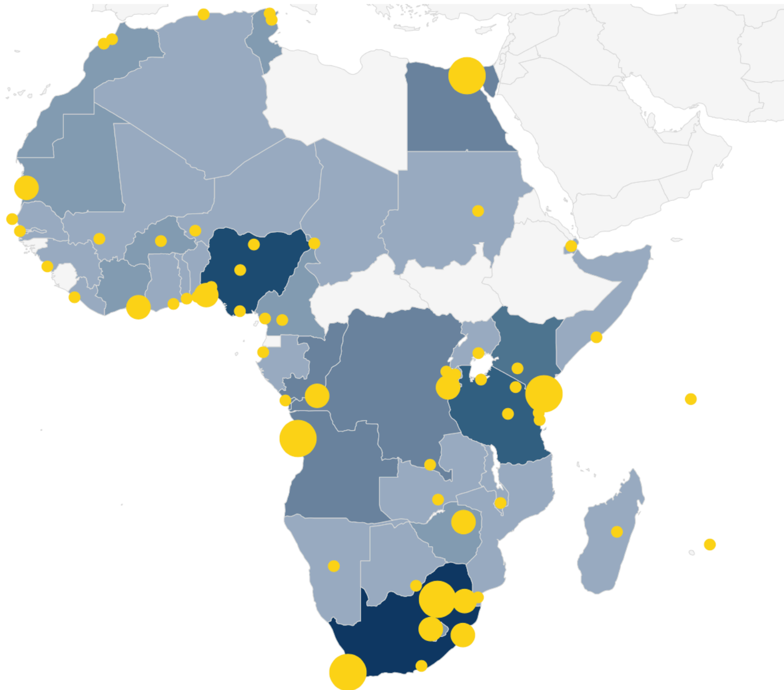


Figure 8.1: Showing 81 IXPs (out of 1082) from Africa - Source: PCH

need for digital services grows, government and private organisations start looking for local alternatives. Local is usually better not only because of potential performance gain, but data sovereignty has become a very important concern for various nations across the globe [190]. In a well-developed ecosystem such in South Africa, there is a flourishing data centre market, whereby the DCs are carrier-neutral and provide multi-tenant colocation facilities. Independent and open DCs tend to attract cloud service providers, CDNs and other content providers as they are given the freedom to choose how and with whom they want to interconnect.

8.2 Localised Internet infrastructure readiness

The study in Chapter 5 provided empirical evidence on the current configuration of web content hosting, access, and distribution in Africa, and has demonstrated that the status of the African content infrastructure is alarming. As also seen in Chapter 7, the poor state of cross-border connectivity between several African states, negatively impacted latency and the overall Quality of Experience (QoE) of the end-users. That is mostly because many African countries heavily rely on foreign services, both to host, to access, and to distribute local content in Africa. Latency levels to remotely hosted local content are high as well as costs of accessing remotely hosted local content.

Most of the public policy strategies on improving local content in Africa focused on demand-side interventions, such as the creation of content in local languages, and on developing skills in web content production and consumption. While these policies are important, bodies in charge of the governance of the Internet are urged to identify ways of facilitating local markets for content hosting, access and distributions by focusing on: (1) incentivising investments in data centres and web farms in Africa, to stimulate economies of scale for the local web hosting market; (2) encouraging local news websites to move the content closer to the users in Africa, by encouraging the use of CDN-enabled networks and by reducing prices for local hosting, (3) facilitating peering relationships between Internet Service Providers (ISPs) and investing in local exchange points to reduce latency; (4) facilitating ISPs to peer in local exchange points and (5) supporting local and regional content hosting/data exchange through a proper regulatory framework.

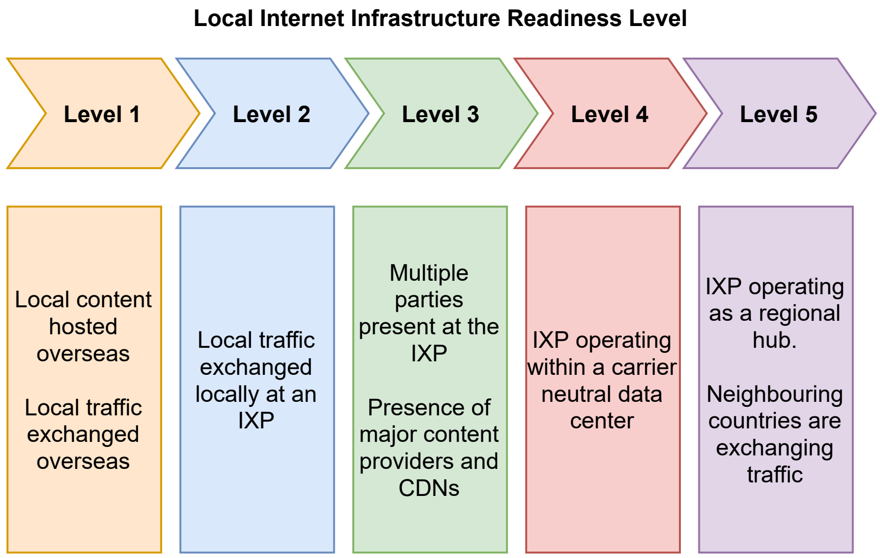


Figure 8.2: Localised Internet infrastructure readiness level

The points above conceptualise the different maturity level of a localised Internet Infrastructure. There are 5 maturity levels as summarised by figure 8.2. Table 8.1 provides a list of IXPs and their respective level of development. This model extends the 3-stage development model as proposed by the IXP impact assessment report by the Internet Society in 2020 [110].

8.2.1 IXP stages of development

Level 1: No IXP At this stage, either there is no IXP or the IXP in the country is not being operated properly. This means that local data cannot be exchanged locally between ISPs and there is a need to use international connectivity for such traffic exchange. Additionally, local content such as news or government websites are hosted externally due to a lack of hosting facilities. Such a situation can lead to high costs of transit which are then cascaded back to the end-users.

Level 2: Presence of an IXP When ISPs have understood the importance of cooperative peering as a means to improve performance, reduce costs and increase the reliability and robustness of the local ecosystem, there is a gradual shift in the traffic pattern. Less use of international bandwidth for local content exchange and the presence of a well-functioning IXP helps to attract global players such as content providers and CDNs. Thanks to the increase in local traffic exchange, end-users also benefit from lower latency and an improved QoE. However, the presence of an exchange point does not itself mean the existence of a strong peering fabric. It depends on how many ASes in the country are peering and actually exchanging traffic. In developing regions, there is usually have one big incumbent operator and smaller ISPs. Whilst, cooperation between smaller ISPs may exist, the incumbent operator, which usually harbour content caches are reluctant to exchange traffic outside of their transit agreements.

Level 3: Presence of CDNs As seen in the previous research, the need to access online content especially multimedia content has risen dramatically[191, 192]. It therefore makes sense to localise the storage of content as close as possible to the end-users. The above is even more important for end-users in low and middle-income countries, where access to the Internet is in many places still unaffordable[189]. Having an IXP, contributes to having a more competitive wholesale transit market, as ISPs have different alternatives to upstream traffic. Additionally, local users can benefit from an increase in capacity (more bandwidth, lower latency) as well as lower port costs at for local traffic exchange. Therefore, a diversity of networks peering at the local IXP and the participation of content providers as peers, would have a positive impact on the growth of traffic and Internet resilience in general.

At Level 3, there is often the presence of CDNs and other networks caches such as GGC (Google caches) or Netflix Open Connect. These are physical devices placed at strategic locations such as within the premises of an ISP or in a data centre close to an IXP, where other networks can have easy access. CDNs and content caches help reduce drastically video content buffering or page loading times and therefore improve the overall QoE of the end-user. By keeping traffic local, they reduce the dependency on international bandwidth usage and by their nature of being distributed, they constitute an effective mechanism against Distributed Denial of Service (DDoS) attacks.

Level 4: Presence at carrier-neutral data centres As the local ecosystem continues to grow, there is a variety of different players (content providers, CDNs, eyeball networks, National Research and Education Networks-NRENs) peering at the exchange point. This is because the main players in a country Internet ecosystem have understood that the importance of localising Internet content. As seen in Chapter 5, in most African countries, the majority of local news websites are hosted offshore. It was also observed how the location of cloud computing services negatively impact the overall Quality of Service (QoS) for the end-user. Localising Internet infrastructure is therefore a key component to would allow government, businesses and other entities to fully take advantage of digital connectivity. To achieve the above, data hosting facilities such as colocation data centres are required. In the past, data centres were tied to the incumbent ISP, leaving no much alternative for content hosting. Nowadays, there is an emergence of carrier-neutral data centres, whereby they only provide hosting facilities without imposing the choice of connectivity provider. Such a model encourages a variety of participants to use the colocation services and having an IXP on such a platform, makes it extremely easy and convenient to peer with the other networks located at the data centre.

Level 5: Regional Integration Similar to the exchange of goods and services within geographical regions, increasing the exchange of information between people and business in neighbouring countries further strengthens regional cooperation. As such, policies to increase international broadband connectivity through cross-border backbones and submarines cables, and services such as mobile RLAH (Roaming Like at Home), are important tools to strengthen regional integration. To increase cross-border data exchange, it is important to increase the availability of international connectivity e.g. through proper investment in regional backbones and submarines cables. Inefficient regional connectivity, such as a lack of peering between ISPs, would also have a negative impact on the quality of service. This is why collaboration between neighbouring countries should be supported by adequate regulatory frameworks, namely through the participation of policy makers and regulators in regional fora. In this regards, IXPs are an important building block for increasing local and regional content exchange and developing a competitive ecosystem for a more robust and affordable Internet. At this level, countries are playing the role of regional hubs and the infrastructure in place is allowing neighbouring countries to exchange traffic.

Table 8.1: Level of development of African IXPs (February 2021)

Name	*Country*	*GDP per capita*	*Geography*	*Networks*	*Level*	*Note*
Harare IX	ZW	1463.99	Landlocked	0	1	Not functional
MLIX	ML	879.01	Landlocked	0	1	Not functional
SoIXP	SO	126.92	Seashore	0	1	Not functional
LuIXP	ZM	1305.06	Landlocked	2	1	Only two networks
SISPA	SZ	3894.68	Landlocked	1	1	One member only
SIXP Sudan	SD	441.51	Seashore	2	1	No local networks
BENIN-IX	BJ	1219.43	Seashore	5	2	Local networks
BFIX	BF	786.9	Landlocked	10	2	Local networks
CGIX	CG	2279.97	Seashore	3	2	Local networks
CIVIX	CI	2276.33	Seashore	11	2	Local networks
IXP Namibia	NA	4957.46	Seashore	5	2	Local networks
IXP-GUINEE	GN	962.84	Seashore	7	2	Local networks
MGIX	MG	523.36	Island	6	2	Local networks
MIX-BT	MW	411.55	Landlocked	4	2	Local networks
MIXP	MU	11099.24	Island	11	2	Local networks
TGIX	TG	679.29	Seashore	5	2	Local networks
RINEX	RW	820.03	Landlocked	10	3	Local networks, CDNs
BDIXP	BI	261.25	Landlocked	9	3	Local networks, CDNs
CAMIX	CM	1507.45	Seashore	9	3	Local networks, CDNs
KINIX	CD	580.72	Seashore	12	3	Local networks, CDNs
Angola IXP	AO	2790.73	Seashore	10	3	Local networks, CDNs
CAS-IX	MA	3204.1	Seashore	3	3	Local networks, CDNs
GABIX	GA	7767.01	Seashore	7	3	Local networks, CDNs
MOZIX	MZ	503.57	Seashore	15	3	Local networks, CDNs
SIXP Gambia	GM	777.81	Seashore	7	3	Local networks, CDNs
UIXP	UG	794.34	Landlocked	29	3	Local networks, Regional Carriers, CDNs
DjIX	DJ	3414.92	Seashore	12	4	International carriers, Data Centre, CDNs
Asteroid	KE	1816.55	Seashore	10	4	Data center, International Carriers, CDNs
TunIXP	TN	3317.45	Seashore	24	5	Local networks, CDNs, Root servers, Regional networks
GIXA	GH	2202.12	Seashore	22	5	Local networks, CDNs, International & Regional Carriers
TIX Tanzania	TZ	1122.12	Seashore	42	5	Local networks, CDNs, Regional Carriers
IXPN Lagos	NG	2229.86	Seashore	61	5	Local networks, International carriers, CDNs
KIXP - Nairobi	KE	1816.55	Seashore	41	5	Local networks, International carriers, CDNs
NAPAfrica IX	ZA	6001.4	Seashore	406	5	Data center, CDNs, International carriers, Local networks

8.2.2 Case studies

This section looks into two African success stories namely Kenya and Nigeria. Both of these countries made tremendous progress to consolidate their local Internet ecosystem by investing into and promoting the development of IXPs .

8.2.2.1 Kenya: a role model for Africa

In the last ten years, Internet penetration in Kenya has increased from 7.2% (2010) to 22.6% (2019) and mobile cellular subscription has increased from 60% (2010) to 103% (2019) as per the World Bank [137]. At the same time, Kenya has made tremendous effort to reduce retail prices to attain 3.10% of Gross National Income (GNI) for 1GB of mobile data, as opposed to more than 10% in 2010[8].

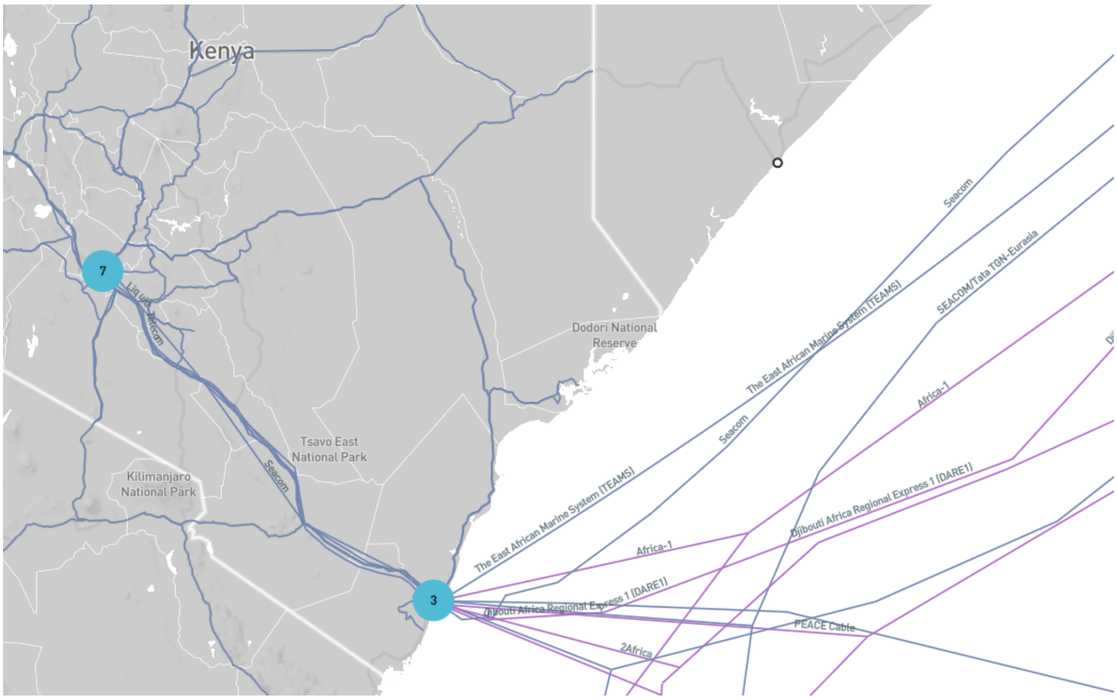


Figure 8.3: Kenya terrestrial and undersea cable systems, with 10 co-location facilities in Nairobi and Mombasa (Feb. 2021). Source: Infrapedia

The Kenya Internet Exchange Point (KIXP) has been initiated in 2000 and is currently managed by TESPOK (the Telecommunications Service Providers Association of Kenya). It initially faced multiple setbacks especially from the incumbent operator (Telkom Kenya) which had a monopoly on international transit. But since KIXP did not intend to provide any transit service, it was allowed to operate initially with five participants.

As per TESPOK[5], until the setup of the KIXP, all Internet traffic was exchanged internationally (with 30% of local traffic). Within only two weeks of operations, KIXP observed a drop in latency from an average of 1200-2000ms (on satellite) to 60-80ms via the exchange point. Incidentally, price for a 64 kbit/s circuit dropped from USD 3375 to USD 200 and for a 512 kbit/s circuit, the price dropped from USD 9546 to USD 650. As per the Internet Society's report by Michael Kende[110], the annual cost saving in 2020 is USD 6 million (was USD 1.4 million in 2012). A summary of changes from 2012 to 2020 is available in Table 8.2.

[5] Technology Service Providers of Kenya, last accessed on 2021-01-14, https://www.tespok.co.ke

Table 8.2: The Internet Ecosystem in Kenya, 2012–2020. Source (Internet Society (ISOC) Report by Michael Kende[110])

		2012	2020
Internet	Internet users	8.80%	17.8% (2017)
	Fixed bb subscribers	0.13%	0.72% (2018)
	Mobile broadband subscribers	0.42%	41.92%
	500MB prepaid (cap)	USD 5.92	USD 2.42 (2017)
	Average download speed		Fixed: 18.17 Mbps Mobile: 21.65 Mbps
IXPs	**KIXP nodes (2000)**	Nairobi, Mombasa	Lagos(4) Abuja Port Hancourt Kano
	Number of peering	25	56
	Peak traffic:	1 Gbps	19 Gbps
	Asteroid IXP (2020)		Mombasa
	Number of members:		10
	Peak traffic:		350Mbps
Infrastructure	Submarine cables	SEACOM (2009) TEAMS (2009) EASSY (2010) LION1 (2012)	SEACOM TEAMS EASSY LION2 DARE1 (2020) Peace Cable (2021) 2Africa (2023)
	International Bandwidth per user (bit/s)	13,932	386,743 (2017)
	IP Transit average price Mbps (GigE, CDR = 1000)	USD 262.50	USD 25.53
Data centers	Carrier-neutral	Internet Solutions	Cloudpap East Africa Data Centre Gestalt Gild Kisumu Mombasa 1 Safaricom
Content Delivery Networks	International	Google Global Cache	Akamai Amazon Web Services Cloudflare Facebook Google Caches Google Edge PoP Microsoft Netflix

International bandwidth also increased with the arrival of new high-speed submarine cables along the coast of Kenya, namely in Mombasa. In 2009, Kenya was mainly using satellite communication for international communication which was very costly and with very high latencies. By the end of 2010, the EASSy, DARE1, SEACOM and TEAMS cables came into picture.

With all major cables landing in Mombasa, KIXP decided to create a PoP (point of presence) on the coast. Additionally, Liquid Telecom which is a pan-African transit provider, invested in a Tier-3 neutral Data centre, the East Africa Data Centre

(EADC). By virtue of the good infrastructure (data centre, cable landing stations, subsea and terrestrial fibre) and a well-functioning IXP, many major CDNs and cloud service providers were attracted to setup their caches to serve the eyeball networks in Kenya (and in the region). This also paved the way to the coming of a privately-operated, neutral colocation facility (iColo). Subsequently, Kenya saw the arrival of new players such as new IXP operators (Asteroid) and major CDNs including Amazon, Google, Facebook and Microsoft.

In terms of *level of development*, KIXP is playing at Level 5 as a regional hub. Many regional carriers that provide backbone capacity for eyeball networks (such as Liquid Telecom and SEACOM) have a presence at the IXP or at the data centre and because of the submarine cables landing in Mombasa, international carriers such as PCCW, China Telecom and Hurricane Electric are also present at the KIXP.

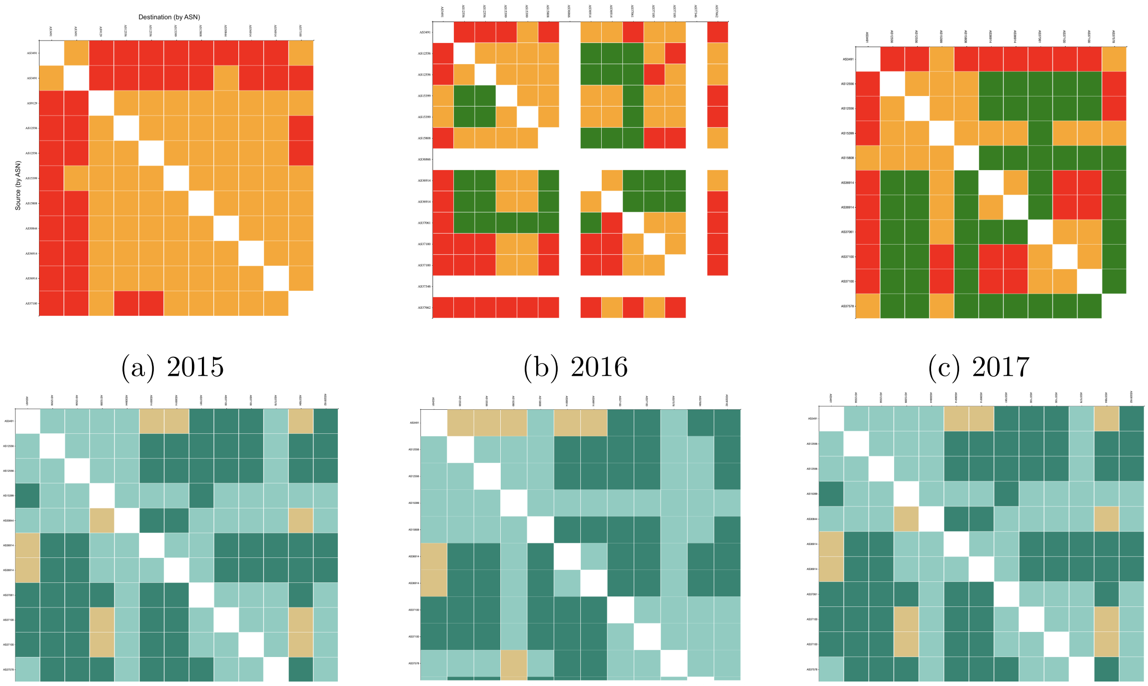
To illustrate the changes that happened in the Kenya Internet landscape from 2012 and 2020, the study makes use of the IXP Country Jedi[6], which is a tool developed by the RIPE NCC, which itself makes use of RIPE Atlas probes located in country to periodical traceroute measurements to other local ASNs. This allows the tool to detect an IXP prefix, a local network or an overseas network, if traffic is exchanged internationally.

As seen in figure 8.4, in 2015, even with the presence of the KIXP, not all ASNs in Kenya were peering with one another (red square), but many had private peering agreements between themselves (orange squares). After 2012, the KIXP decided to drop the Mandatory Multilateral Peering Agreement (MMLPA) which was forcing the participants to peer with all other participants at the IXP. This rule has been relaxed.

From 2015-2017, a dark green square signifies that traffic stays local and no out-of-country Internet Protocol addresses (IPs) were found. An orange squares means a direct relationship between the two Autonomous System Number (ASN) (no IXP and no out-of-country IPs found) and the red square means no IXP and out-of-country IPs used to reach the destination AS.

From 2018-2021, the colour scheme changes a little. A dark green square still signifies that traffic stays local and no out-of-country IPs, while a light green square signifies no IXP founds and out-country IPs were not found. Finally, an ochre square means no IXP found in the path and out-of-country IPs were used to reach the destination AS (i.e. circuitous routing).

[6]RIPE IXP Country Jedi, last accessed on 2021-01-12, https://www.ripe.net/analyse/internet-measurements/ixp-country-jedi



(a) 2015 (b) 2016 (c) 2017

(d) 2018 (e) 2019 (f) 2020

Figure 8.4: Peering evolution at the KIXP. (X-Axis: Source ASN, Y-Axis: Destination ASN) IXP Country Jedi uses RIPE Atlas to run traceroute measurements from a *Source AS* to *Destination AS* within the same country. Source: IXP Country Jedi (RIPE Atlas). N.B the colour scheme changed after 2017. Dark green still represents presence of an IXP on the path.

8.2.2.2 Nigeria: a regional hub

IXPN (IXP of Nigeria) can also be considered as a role model for Africa with regards to the growth of the services and the diversity of participants present at the exchange point. Similar to Kenya, Nigeria has experienced a rather steep adoption of mobile broadband in the last ten years. As per the GSM Association (GSMA) 2020 report[26], 78% of the population is now covered with 3G connectivity as opposed to 21% in 2010. The Nigerian market represents more than 100 million mobile subscribers, making Nigeria the largest market for mobile broadband in Africa.

In a recent report from the World Bank and the GSMA[193], they studied the impact of mobile broadband on poverty reduction in Nigeria, they found that the proportion of households below the poverty line (USD 1.90) drops by about 4% in a year of having mobile broadband access and by almost 7% in two years of having mobile broadband access. In short, mobile technology, in particular mobile broadband, can play a significant role in reducing poverty and increasing economic opportunities

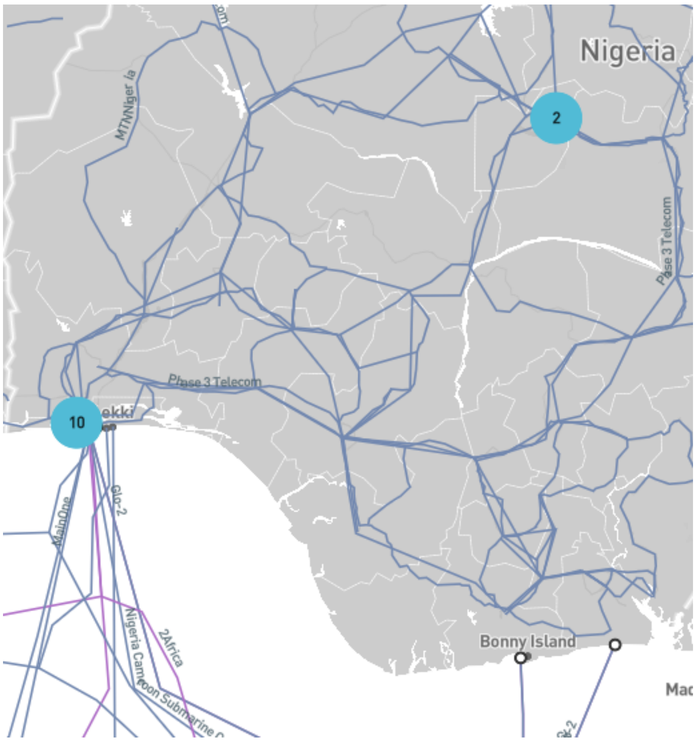


Figure 8.5: Nigeria terrestrial and undersea cable systems with 12 co-location facilities (Feb. 2021). Source: Infrapedia

in developing and least-developed countries.

As such, to cater for the increase on the demand-side, Nigeria invested massively in the national backbone infrastructure. Nigeria can be considered as a regional hub with multiple submarine cables landing in Lagos. In the last ten years, IXPN moved from Level 2 to Level 5 in terms of development of the local Internet ecosystem. With only two submarine cables landing in 2012, there are currently seven cables providing international connectivity to the region. A summary of changes from 2012 to 2020 is available in Table 8.3.

The proximity with the cable landing stations in Lagos, makes the city an ideal place to host content caches that will serve the entire region, especially the networks served by the main regional carriers e.g. MainOne. Instead of using private interconnects to connect the different data centres, the CDNs would naturally prefer to use the IXPN network to reach out to the different eyeball networks which are also incentivised to connect to the IXP. This becomes a win-win situation for the different players: more hosts at the data centres, more peers at the IXP, reduced latency and cost savings on the international links. Similarly, as the Kenyan IXP, IXPN allows any participant to interconnect to one another on a need-basis, removing the mandatory multilateral peering agreement, where everyone needs to interconnect with all the other participants.

As more and more players came in to consolidate Lagos as regional hub, there was a need to diversify the peering facilities. In 2018, a new IXP, the West African Internet Exchange (WAF-IX), with the support of Asteroid, established business in the Lagos area with the aim so serve the Western African countries.

Table 8.3: The Internet Ecosystem in Nigeria, 2012–2020. Source (ISOC Report by Michael Kende[110])

		2012	**2020**
Internet	Internet users	0.161	0.42
	Fixed bb subscribers	0.0001	0.0004
	Mobile broadband subscribers	0.0679	0.3068
	500MB prepaid (cap)	USD 12.75	USD 3.27
	Average download speed		Fixed: 11.93 Mbps Mobile: 16.04 Mbps
IXPs	**IXPN nodes (2006)**	Lagos	Lagos(4) Abuja Port Hancourt Kano
	Number of peering networks	30	71
	Peak traffic	300 Mbps	125 Gbps
	WAF-IX nodes (2018)		Lagos
	Number of peering networks		15
	Peak traffic		11Gbps
Infrastructure	Submarine cables	SAT3 (2002) Glo-1 (2010) Main One (2010)	SAT3 Glo-1 Main One WACS (May 2012) ACE (December 2012) Glo-2 (2020) Equiano (2021)
	International Bandwidth per user (bit/s)	5341	2255
	IP Transit average price Mbps (GigE, CDR = 1000)	USD 450	USD 27.45
Data centres	Carrier-neutral		Excelsimo Galaxy Backbone ICN ipNX Layer3 Madallion Comm MDXi data centres (2) Rack Centre
Content Delivery Networks	International	Google Global Cache	Akamai Amazon Web Services Cloudflare Facebook Google Caches Google Edge PoP Limelight Microsoft Netflix

8.3 Factors impacting the development of IXPs

8.3.1 Bandwidth and latency

The development of IXPs can be evaluated through different indicators e.g. country average available bandwidth on fixed-broadband, average latency and access to fixed-broadband[7]. Figure 8.6 shows the number of IXPs per 10M inhabitants for each region overlaid with the average latency to major websites as well as the affordability of mobile services - calculated as a percentage of the GNI.

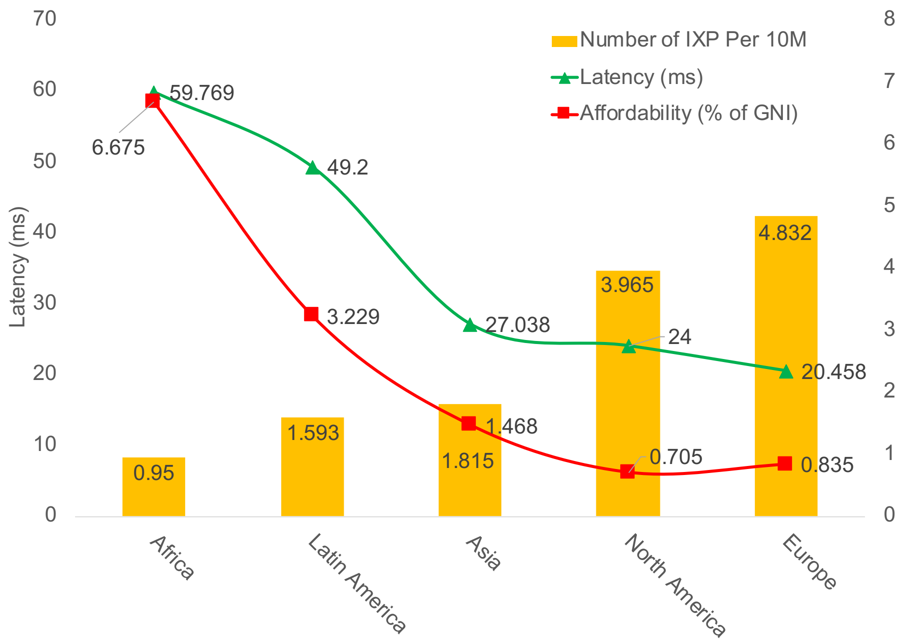


Figure 8.6: Number of IXPs by region (shown per 10M inhabitants). On the left Y-axis there is the average latency (Source: EIU Inclusive Internet Index) (in ms) to major websites and on the right Y-axis, there is the average affordability of mobile services taken by percentage of the monthly income. Source: Economist Intelligence Unit's Inclusiveness Index 2020 from: https://theinclusiveinternet.eiu.com (accessed 04 February 2021)

To understand the factors affecting the development of IXPs, indicators were retrieved from the Economist Intelligence Unit's (EIU) Inclusive Internet Index[194] which is a public dataset of different indicators used to calculate a country's "Internet inclusiveness". Using other public sources of data such as PeeringDB[8], CAIDA[9] and

[7]In regions where mobile connectivity is predominant, e.g. Africa, mobile indicators such as average mobile download speed, latency on mobile services and access and affordability to mobile broadband would be of relevance.

[8]Peering DB, last accessed on 2021-02-15, https://www.peeringdb.com/

[9]CAIDA IXP database, last accessed on 2021-02-15, https://www.caida.org/data/ixps/

PCH[10], this study built a repository of IXPs around the world. The EIU dataset categorises the countries by level of income (high-income, middle-income and low-income countries).

Without much surprise, 60% of all IXPs in the world were located in higher-income countries while 15% are located in low and middle-income countries (LMICs). Looking into the 78 LMICs, 24 countries did not have an IXP and out of which, three countries in Africa were landlocked without direct access to the submarine cable ecosystem. In Africa, three countries had an ISP monopoly with the incumbent operator running the telecommunication infrastructure, these were Djibouti, Ethiopia and Eritrea. It is interesting to note that Eritrea is one of the only coastal countries in Africa without any cable landing stations. To summarise, as compared to other more developed regions, the development of IXPs (per 10M) was still lagging behind in Africa.

In a previous study, Galperin *et al.* provide evidence on the impact of implementing an IXP in Bolivia. Their results show a positive impact on network performance nationwide. More specifically, local traffic passing through the exchange (PIT Bolivia), exhibits lower latency and goes through fewer hops as opposed to local traffic routed over international links [102]. The data gathered by EIU confirmed this trend, the higher the number of IXPs per 10M inhabitants, the lower the latency is in general. The average latency on fixed broadband was lowest in the APAC (Asia and the Pacific) region (26 ms) and highest in the African region (54 ms). Regarding mobile broadband, the trends were very similar with an average of 69ms in Africa, 52 ms in Asia-Pacific, 55 ms in Latin America, 49 ms in North American and the lowest being in Europe (34 ms).

8.3.2 Availability of co-location facilities

As mentioned before, another important component of a robust national data infrastructure is the presence of co-location data centres. For this we use the Datacentermap[11], which provides the number, type and location of colocation facilities around the world. Without much surprise, most co-location facilities were concentrated in North America (ARIN), Europe (RIPE NCC) and the Asia Pacific (APNIC) regions. Africa (AFRINIC) and Latin America (LACNIC) were very comparable in terms of

[10] Packet Clearing House IXP directory, last accessed on 2021-02-15, `https://www.pch.net/ixp/dir`

[11] https://www.datacentermap.com/datacenters.html - accessed February 2021

the number of co-location facilities and the evolution from the last ten years as shown in figure 8.7

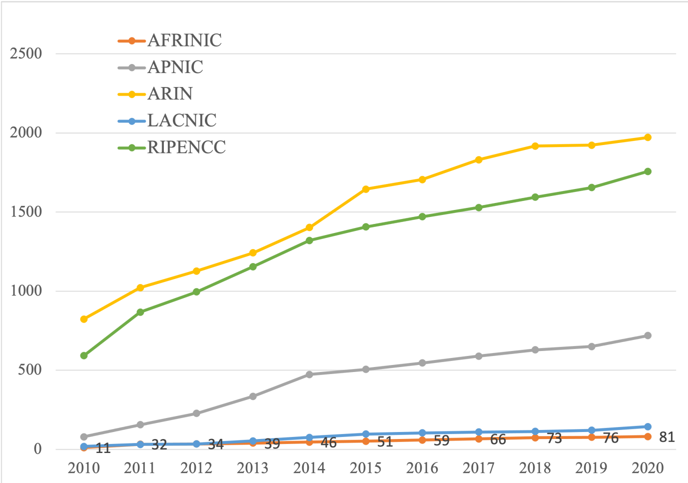


Figure 8.7: Currently there are 4740 colocation data centres from 127 countries in the world, with only 81 in 14 African countries (2021). Source: Datacentermap

The number of co-location facilities, especially carrier-neutral data centres, reflects the maturity of the national ecosystem. Teraco[12] in South Africa and iColo[13] in Kenya are notable success stories with regards to carrier-neutral data centres. Not only have they attracted the local networks and fostered the growth of co-located IXPs (e.g. Asteroid and NapAfrica), they have attracted major CDNs players to operate their edge caches and also encouraged content providers to set up PoPs in the data centre.

8.3.3 IXP and concentration

Another factor that can stymie the development and growth of IXPs is the presence of monopolistic ASes. Some countries without an IXP, still had their Internet infrastructure being managed exclusively by the dominant operator. In order to determine if there was any concentration with regards to the distribution and usage of IP addresses, data from the CAIDA's *pfix2as* files (February 2021) and the AFRINIC delegated files[14] were collected. Both of these datasets helped to select a list of ASNs that were appearing in the routing table.

The study calculated the *level of concentration* by computing the Herfindahl-Hirschman Index (HHI), which is a statistical measure of concentration (0 to 1),

[12] Teraco Data Centres, last accessed on 2021-08-01, https://www.teraco.co.za
[13] iColo Data Centres, last accessed on 2021-08-01, https://www.icolo.io
[14] AFRINIC Delegated files, last accessed on 2021-01-13, http://ftp.afrinic.net/pub/stats/afrinic/delegated-afrinic-extended-latest

where 0 means no concentration and 1 means full concentration on a single network. Figure 8.8 shows the HHI distribution for some African countries (those with at least 1M allocated IP addresses were selected to focus on the larger economies). The countries with a high HHI were: Algeria, Ivory Coast, Uganda and Zambia and those with the lowest HHI value were Tunisia (TN), Seychelles (SC), South Africa (ZA) and Nigeria (NG). HHI index is defined as follow, where s_n is the market share (%) of the ASN in the country c:

$$HHI_c = s_1^2 + s_2^2 + s_3^2 + ... + s_n^2$$

With regards to the stages of development, Algeria and Zambia were still at Level 1 i.e. No IXP or defunct IXP. For Ivory Coast and Uganda, it is interesting to see that there was a dominating player in each of these countries, even if there was an operational IXP. On the other hand, it can be observed how a diversity of players decreased concentration (HHI < 0.5). Examples of such countries are Kenya (KE), Ghana (GH), Tanzania (TZ), Tunisia (TN), South Africa (ZA) and Nigeria (NG).

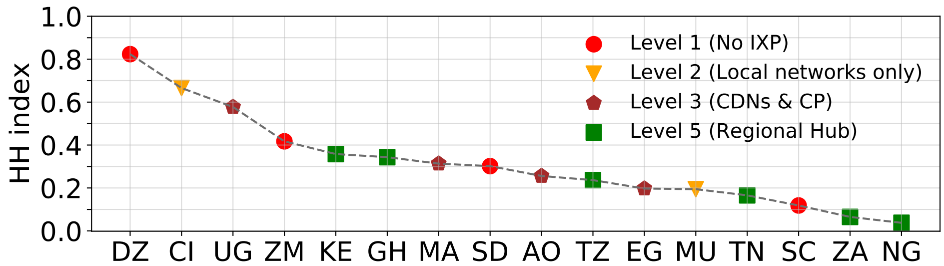


Figure 8.8: Usage of the HHI to determine the level of concentration for countries with at least 1M IP addresses. HHI has been normalized between 0 an 1.

8.4 Estimating the impact of IXP on local content development

The relationship between the presence of IXPs and the efficiency of data traffic exchange within a country [102, 111] has been empirically proven in previous literature. However, little is known about the actual impact of IXPs on local content development. In this section, an analytical framework is defined, based on the fixed-effect statistical model to estimate the impact of IXPs on local content activity.

8.4.1 Evaluation model

To estimate the impact of IXPs on *local content activity*, this study hypothesises that the latter is directly relational to the *scale of the IXP*, measured quantitatively by the number of Autonomous Systems (ASs) present at the IXP. Therefore, the main independent variable is the ratio of ASs in a country participating to the local IXP and the dependent variables are the set of indicators of local content activity (LCA) as identified in Table 8.4 i.e., the number of domains under a ccTLD and the number of web pages indexed by Google (both reduced per capita). The number of domains under a ccTLD is usually reflective of the local content activity as many local businesses would use the ccTLD to carry out their operations (e.g. e-commerce, news, government agencies, etc.). Similarly, the number of pages under a ccTLD provides a good indication whether the content is local. Google web search provided the number of web pages indexed by domain. For this an index called the *LCA index* is defined as follows, where i refers to Country i in year t:

$$LCA_{i,t} = \ln(domainCount_{i,t} * webCount_{i,t}) \tag{8.1}$$

However, local content activity (LCA) within a country is influenced by other factors such as physical connectivity, available bandwidth or network coverage. Other factors such as GDP, population size of the country as well as the existence of a conducive national broadband strategy should be factored in - as they contribute to an enabling environment. As mentioned earlier, countries with higher income tend to have a more mature local Internet ecosystem, usually with one or more operational IXPs and with a high percentage of participating ASs. This study collected data by country and over the last five years. The dataset was therefore both longitudinal and multi-dimensional, also known as panel data[195].

Table 8.4: Country-level indicators of local content activity (dependent variables)

#	Variables	Description
1	Domains under ccTLD	The number of domains registered under a country-code TLD. This metric shows the domain-related activities in a country. Normally websites with a ccTLD domain are meant for local consumption. *Source: https://research.domaintools.com/statistics/tld-counts/*
2	web pages indexed by Google	The number of web pages indexed by Google by country. It is possible to retrieve the number of pages indexed by Google by ccTLD. This provides an indication of the amount of local content indexed and accessible. *Source: Google Web Search*

Since the study was dealing with panel data, it made use of a linear regression model to define the relationship between the *local content activity* and the scale an IXP as the following:

$$\begin{aligned} LCA_{i,t} = \alpha_i + \beta_1 IXP_{i,t} + \beta_2 HHI_{i,t} + \beta_3 BW_{i,t} \\ + \beta_4 CS_{i,t} + \beta_5 GDP_{i,t} + \beta_6 IPv4_{i,t} + \beta_7 NC_{i,t} + \epsilon_{i,t} \\ i = 1, 2, ..., N; t = 1, 2, ..., T \end{aligned} \tag{8.2}$$

where $LCA_{i,t}$ is the natural logarithm of the domain count (dependent variable 1) and the number of web pages indexed by Google (dependent variable 2) in country i at time t. The control variables are defined in Table 8.5 and the data was compiled from the Economist's Inclusiveness Index[194]. Since the distribution of the variables were asymmetric, the natural logarithm was used instead. $\alpha_{i,t}$ is defined as the unknown intercept for country i and an error variable for all data missing for country i at year t in the dataset was introduced.

Table 8.5: Description of control variables

Variable	**Description of variable at country i at year t**
α	An unknown intercept
ϵ	An error value representing the effect of missing variables by the model
IXP	IXP scale: percentage of ASs present at the IXP
BW	Available bandwidth in bits/s by Internet user
HHI	Herfindahl-Hirschman Index for the country
CS	Number of cables landing stations per 10M inhabitants
GDP	Economic development represented in GDP per capita
IPv4	IPv4 allocation per capita
NC	% of population covered by a 3G network

To validate this model, the relationship between the independent, dependent and control variables were tested using the fixed-effects method[196, 197], a technique borrowed from econometric literature to observe the effects of the variables over time. In a recent study, Falk *et al.* used a similar approach to determine the impact of high-speed broadband on local establishment dynamics[198].

Furthermore, to make sure the study was using the right approach (i.e. fixed effects vs random-effects) on the panel data and to see whether there was a correlation (or lack thereof) between the observed variables and unobserved variables, a *Hausman test*[199] was carried out. The *p-value* being less 0.05 (0.41652), the null hypothesis, which was using the random-effects model as preferred approach, was discarded.

8.4.2 Data and results

The aim of this study was to assess the relationship between the growth of IXPs and the *local Internet activity* in 26 African countries over a period of 5 years i.e. between 2016 and 2020. To obtain the panel data, several sources of information, namely the PCH IXP directory[48] and the Economist's Inclusive Internet Index[194], and the DomainTools[15] were investigated.

For this analysis, a list of countries operating at Level 2 and above (see Figure 8.2 i.e. where an IXP is present) was chosen. The aim was to see over a period of time, if the change in the number of ASs peering at the IXP had an impact on the overall *local content activity* of a country. 26 African countries were selected[16] with a least one operational IXP. The number of peers participating at the IXP was extracted and the ratio of peers vs the number of ASNs allocated to the country was determined.

To calculate the "local content activity" of a country, the study first collected data from the DomainTools portal which provided live statistics on (dep. var. 1) the number of domains per TLD. Then using the Internet Wayback Machine[17], data from the DomainTools website were captured since 2016. Then, to obtain (dep. var. 2) the number of pages indexed by Google, this study relied on the information provided by the Google Search[18] functionality. Datasets before 2020 were crowd-sourced from previous studies, namely from the Africa DNS Market Study[200]. Since the countries had different population sizes, the dataset was normalised by the population size.

For the control variables (see list in table 8.5), the study retrieved data from the Economist Intelligence Unit's "Inclusive Internet Index"[19]. The latter provided an exhaustive list of more than 50 indicators under four main categories: availability; affordability; relevance and readiness.

This study first checked the relationship between the *local content activity* and the relative *scale of the IXP* (measured in terms of the ratio of participating peers and the number of allocated ASNs in a country). As it can be seen from figure 8.9, there was a positive correlation (Pearson coefficient of 0.157324) between the scale of the IXP and the LCA index. Countries such as South Africa and Mauritius were

[15] DomainTools, last accessed on 2021-04-28, https://www.domaintools.com/

[16] A few countries, namely: .bi, .ml, .tk, .gq, .ga and .cf, were removed from the datasets. Some of these African ccTLDs are used by the Freenom registry and are given out for free. The domain count for these ccTLDs was much higher than the average of domains therefore would have skewed the analysis.

[17] Web Archives, last accessed on 2021-03-24, https://archive.org/web/

[18] https://www.google.com/search?q=site:<.cctld>

[19] Facebook/Economist Inclusive Internet Index, last accessed on 2021-04-28, https://theinclusiveinternet.eiu.com

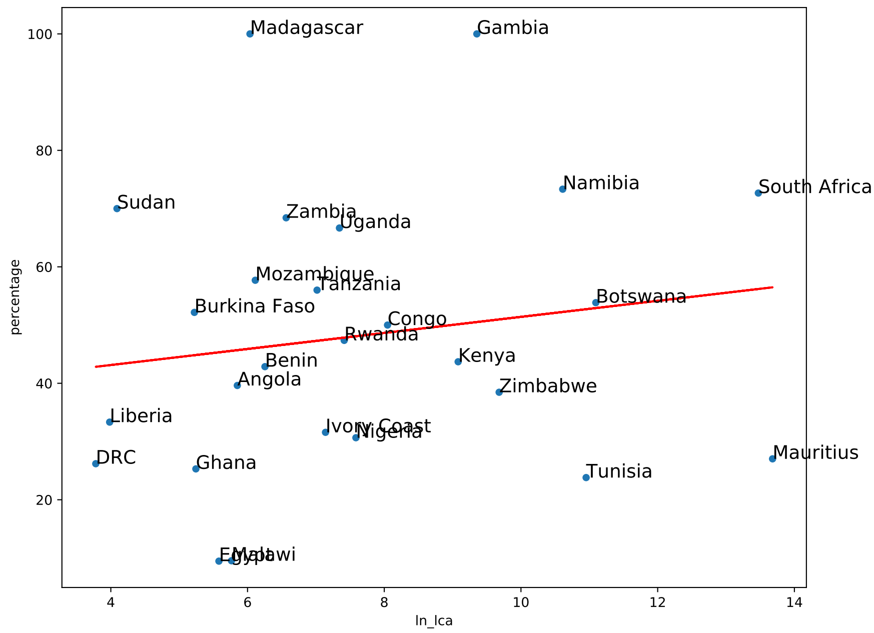


Figure 8.9: IXP scale (%) vs LCA (Local Content Activity)

leading in terms of *local content activity* followed by the Gambia, Namibia, Tunisia and Botswana. For South Africa, more than 75% of the ASs were participating at the local IXP (NapAfrica).

However, if a simple linear regression is performed, the study produced a negative coefficient for *ixp_scale* (which is the log-transformed percentage of participating ASs at an IXP). This is a little counter-intuitive since it meant that the bigger the scale of the IXP, the lower the level of *local content activity* in that country. This may come from multiple factors such as omitted variables. If the *ixp_scale* was correlated with country fixed-effects or time fixed-effects or idiosyncratic error, this would have introduced some bias in the estimates.

The best way therefore was to proceed with the fixed-effects econometric model to control the other variables (see table 8.5), and to evaluate the relationship between the IXP scale (%) and the local content activity LCA. The estimation results are shown in table 8.7 where a positive correlation between lca and the scale of an IXP, measured in the percentage of participating ASs, could be seen. So for any 10% increase in the "scale of an IXP", there was a $(1.10^{0.228} - 1) * 100 = 2.18\%$ increase in the LCA index.

Table 8.6: Simple regression on *lca* and *ixp_scale*

	Dependent variable:
	Local Content Activity (Log)
IXP scale in percentage (Log)	-0.334^{*}
	(0.177)
Constant	4.806^{***}
	(0.676)
Observations	99
R^2	0.035
Adjusted R^2	0.025
Residual Std. Error	1.251 (df = 97)
F Statistic	3.539^{*} (df = 1; 97)
Note:	*p<0.1; **p<0.05; ***p<0.01

Additionally, the results indicated that local content activity (LCA) was positively correlated with bandwidth (BW), the number of cable landing stations (CS), the country's GDP(GDP), though statistically insignificant. A very important component of a resilient Internet infrastructure is the cross-border connectivity. The more the number of cable landing stations or the number of cross-border fibre connections available, the more stable a country would be in terms of bandwidth and latency, which are factors that influence the operations of data centres and in-country cloud-based services.

The control variable with which the correlation is the most statistically significant was $IPv4\_100$ which represented the number of IPv4 addresses per 100 inhabitants. The estimation has therefore provided empirical evidence that the number IP addresses in use within a country had a direct impact on the *local content activity* of that country. It can be observed that there was a negative correlation with the country's Herfindahl-Hirschman Index of IP address allocation, which confirmed the hypothesis in 8.3.3 that the higher the concentration/dominance of monopolistic ASNs, the lower the development of the IXP and incidentally the lower the LCA.

Interestingly, the LCA index was negatively correlated with the 3G coverage per 100 inhabitant control variable. This could be explained by the fact that even if users in Africa countries have 3G coverage, access to Internet services is still very unaffordable. Therefore, there was no direct relationship between network coverage and local content activity, which was not the case for other regions of the world such as the EU or the US.

Finally, GDP (USD million) was introduced in the model as it is often used as a proxy for market size and economic activity. It was found to be positively correlated, without significance. Previous studies showed a direct relationship between high-speed Internet access and GDP growth[201, 202], in particular, when there is an increase on the demand-side (end-users), there is an immediate impact on the supply-side (network operators), therefore an increase in Internet infrastructure investment is observed.

Table 8.7: Fixed-effects estimation results

	Dependent variable:
	Local Content Activity (Log)
IXP: IXP scale in percentage (Log)	0.226^{**}
	(0.117)
BW: Bandwidth (Log)	0.098
	(0.107)
HHI: Herfindahl-Hirschman Index (Log)	-0.338
	(0.508)
CS: Number of cable landing stations per 10 million inhabitants	0.057
	(0.166)
GDP: GDP in million USD (Log)	0.116
	(0.347)
$IPv4$: Number of IPv4 addresses per 100 inhabitants (Log)	1.024^{***}
	(0.365)
NC: Percentage of mobile network coverage in 3G (Log)	−0.021
	(0.455)
Observations	96
R^2	0.164
Adjusted R^2	−0.168
F Statistic	2.228^{*} (df = 6; 68)
Note:	*p<0.1; **p<0.05; ***p<0.01

8.5 Policy considerations

This chapter studied the different factors that can impact the growth of a country's digital ecosystem. The availability of good backbone and last-mile infrastructure, a competitive market structure and the presence of localised Internet infrastructure are the key elements that contribute to a resilient Internet ecosystem. In order to create an enabling environment that would attract more players and create new business opportunities, it must be supported by the relevant policies and regulations. Not only these policies should foster growth of the existing infrastructure and market, but they should be inclusive to ensure affordable and equitable Internet coverage e.g. in rural areas. Therefore, all the stakeholders whether it is the government, the private sector, the civil society or the end user, have an important role to play. One of the core insights from the chapter was that countries at different stages can face vastly different challenges, and therefore policy and investments must be tailored to their context to address existing challenges.

In Africa, 20 countries do not have an IXP yet and 6 countries have attempted to run an exchange point without much success (i.e. operating at Level 1). Only 14 countries have data centres in Africa, with more than 50% concentrated in well-connected hubs (Lagos, Johannesburg, Mombasa, Luanda). As it could be seen in some places, there is a direct relationship between the cable system landing and the presence of co-location data centres (e.g. Mombasa or Lagos). Unfortunately, the landscape is very different for some land-locked countries, where there are no such vibrant activities mainly because of an uncompetitive market, lack of collaboration between ISPs and other players, poor telecommunication policies and restrictive regulations with regards to the operations of data networks in a country. Usually, for some of the countries operating at Level 1 (No IXP or defunct IXP), the regulator can force all participants to adopt a specific interconnectivity regime, mainly to enforce more control by allowing a single monopolistic ISP (most of the time state-owned) to provide upstream connectivity (e.g. Ethiopia). This contributes to slow down the growth of the local Internet ecosystem. As highlighted in this thesis, countries such as Eritrea or Ethiopia, may require other fundamental market reforms prior to investments in data infrastructure. For data infrastructure such as exchange points to be present, a market with several competitive participants is key. Market size and lack of domestic data exchange and hosting may also be reasons for the presence of robust data infrastructure. That can become a chicken-and-egg problem – investments in Internet exchanges can at times galvanise the local data flows in smaller markets due to latency gains, and where market conditions allow, can and should be considered for set up.

Countries with an IXP but without participant diversity – those comprising Level 2 – seem to share a different set of challenges. First, the case studies empirically demonstrate that the presence of an IXP even without additional storage infrastructure can yield benefits by localising data flows. However, these IXPs can face challenges in terms of growth and scale, especially in a scenario of growth in content consumption. This study highlighted that restrictions in the type of networks allowed at IXPs are not beneficial to the effective functioning of national data infrastructure and subsequent growth of the digital ecosystem. Restrictions on the co-location of content delivery networks and IXPs really makes a difference to the growth in traffic.

The role of IXPs has also transformed from just keeping domestic traffic within the country to attracting global content providers, further reducing the need for international bandwidth and generating demand for colocation data centres. To capture this element, Level 3 comprises countries that do not just have a basic and functioning IXP, but one that has participant diversity and attracts content hosting and large content providers as peers. Other constraints to increasing participant diversity may be in the form of restrictive regulations that mandate peering of certain kinds of operators only at the IXP. Research from countries like Egypt suggests that the presence of the IXP can be restricted to domestic Internet Service Providers by government regulations, which also constrains the growth of the IXP in terms of participant diversity, and eventually, stymies the growth of the Internet ecosystem overall.

Level 4 and 5 feature diverse participants including not only local ISPs but also regional and international ISPs, content providers and colocation in a neutral data centre. Only 8 countries in Africa meet these criteria; Kenya and Nigeria were studied in detail. Both countries took some time to reach this stage; for instance, two decades were needed for the Kenyan IXP KIXP. These experiences demonstrate that an IXP needs to be in operation for some years to develop expertise and create trust and galvanise an ecosystem of peers for a more vibrant data ecosystem. The evidence suggests that some time may need to pass before an IXP can evolve to a higher stage. This process may be accelerated by eliminating other constraints to growth, especially those pertaining to policy regimes and regulations.

Another key element is the governance structures that enable the best utilisation of existing data infrastructure. Neutrality of the location of the IXP, openness to participants, transparency in operations and ease of use for all participants inspires trust among peers and galvanises more participation.

The case studies show significant heterogeneity in their ownership structures. While most IXPs are operated on a non-profit basis, operational ownership by other stakeholders including government and industry associations (Kenya and Tanzania) are possible. Two of the IXPs studied are operated on a for-profit basis (Kenya and Nigeria). To the extent that the ownership vests with government, they can play a supportive or adversarial role in the growth of the data infrastructure within a country. Government regulations can both help and impede IXPs for example where ISPs may be reluctant to participate. They can either “force” connectivity through legislation or, they can inspire trust and attract investment by adopting data protection laws such as in Kenya.

Another outcome of this study is that being located at the top of the ladder does not imply enjoying all the benefits of a modern digital infrastructure. Existence of infrastructure alone may not be enough to determine whether it can bring domestic benefits. Djibouti illustrates this point well, as a country which sits at the top of the data infrastructure ladder, whose citizens do not benefit from the existence of the advanced infrastructure. This goes on to show the importance of openness and access to infrastructure as key to realising benefits, beyond mere presence. Structural market changes may be required for the material benefits to be equitably shared amongst all domestic participants.

While an IXP can help to reduce Internet prices due to lesser reliance on international bandwidth, this needs to be accompanied by retail ISP competition. Countries where mobile data prices are high (relative to incomes), are all monopolies or in the case of Cabo Verde a duopoly. Djibouti is instructive as it has the second-highest prices relative to income despite having an IXP. As noted earlier, there is a single ISP and the IXP is more akin to an international wholesale transit point, in this case.

8.6 Rural IXP as a possible future consideration

The importance and benefits of IXPs are no more to be proven. They have become an indispensable catalyst to increase cooperation between neighbouring networks, reduce latency and improve the overall Quality of Experience (QoE) of the end-users.

As seen in Figure 8.10, the major mainstream IXP are concentrated either in the main cities, where there is a high urban population density or near the cable landing stations along the coast. This is more or less the same configuration in other regions of the world. But in Africa, we do still have a lot of population living in rural areas where sometimes there is little to no means of access to the Internet. Rural broadband alternatives comprising of Wireless Internet Service Provider (WISP), Community Network (CN) or wireless mesh networks are meant to bridge the gap and provide access to the Internet or to a localised network. Unfortunately, such “last-mile access networks” are generally not included, when it comes to national or regional peering,

Figure 8.10: IXPs are mostly located in big cities with high urban population density. Source: Telegeography (April 2021)

usually as they do not have a direct link or a Point of Presence (PoP) to the national IXP.

Irrespective of the available bandwidth available on rural networks, connecting several small community networks could eventually benefit the end-users by keeping local traffic local. A rural IXP would enable hosting of local content for example local news, government health service information, school learning resources, etc. Hosting latency-sensitive applications such as video conference tool, Voice Over IP (VOIP), would definitely encourage school learners or health practitioners to engage interactively with their tutors or patients.

Additionally, similar to *iNethi*, the community network described in Chapter 4, localised cloud-based services, such as file sharing and chat applications can hosted, in addition to more specialised services to enable application such e-farming and e-agriculture. These platforms would deliver low-latency functions that would be impractical using the Internet, with the service located outside of the country. At the same time, network operators can natively deploy latest technologies such as IPv6, so that scalability of the network is ensured. Figure 8.11 provides an illustration of a rural IXP.

In order to ensure an acceptable level of service, rural networks should adopt the same best practices as mainstream networks. There are for example having more than one upstream provider to multi-home for load-balancing and fail-over, a proper

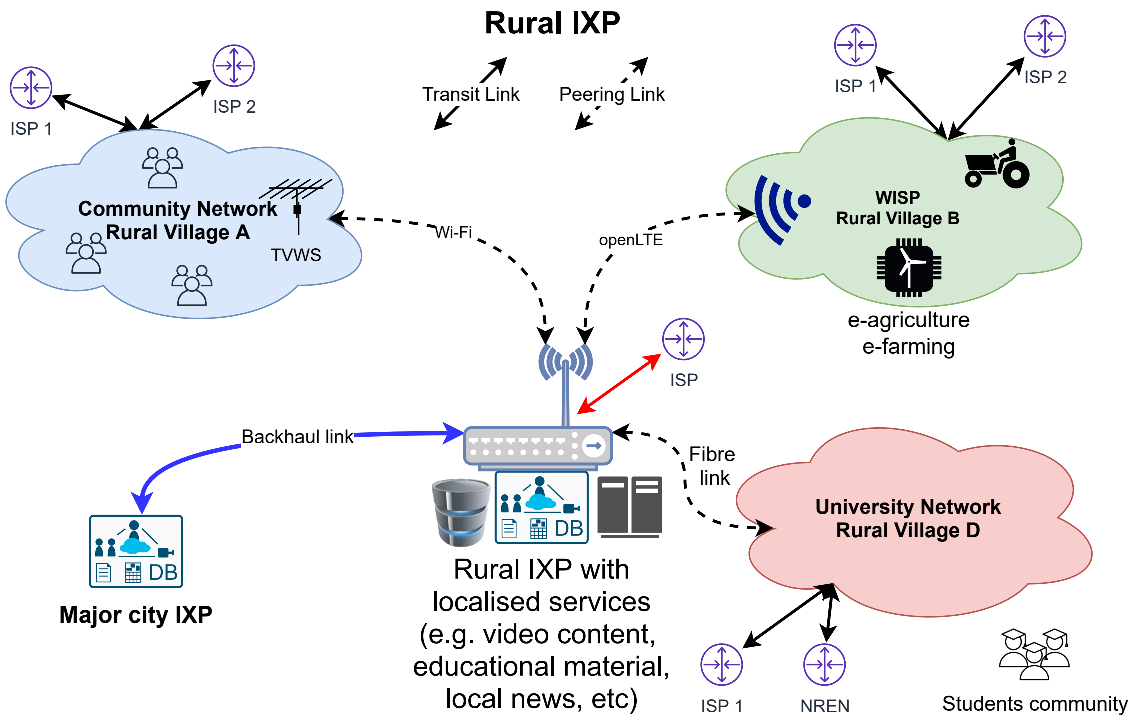


Figure 8.11: Illustration of a rural IXP connected to four different types of rural networks

DNS infrastructure, proper address planning for public services. As such they will be able to connect to the Internet and allow their users to benefit from externally hosted services. Local routing with a rural IXP would allow several rural networks to exchange traffic locally. These are the potential benefits of operating a rural IXP:

- Cut in the transit cost by reducing external bandwidth usage to reach remotely hosted services.
- A rural IXP can play the role of an aggregator by providing easy and fast access to major backhaul towards urban networks and IXPs, where major operators and data centres are present.
- Rural networks can use a variety of access medium such as long-range Wi-Fi, openLTE, TVWS, etc. This means that potentially local services will benefit from large bandwidth capacity.
- With local services hosted on the rural IXP, latency to the local services will be reduced drastically, providing a better Quality of Experience (QoE) to the end-users.

- Such a platform would allow greater usage of ICT service and would act as a catalyst for local content generation and consumption.

Rural IXPs can be operated under different models. WISPs and other rural network operators can form a cooperative and offer IXP service for free, by having the operating costs absorbed by the participating peers. Most advanced places, such as in developed regions, a rural IXP can be a commercial service, where peers need to pay a fee to exchange traffic and benefit from the services provided (direct access to content providers, etc.). In Africa, a district council or a university can play the role of an IXP operator for the subregion. Ideally, each subregion (a district or a conglomerate of rural settlements) can form the required catchment area for an IXP. Network operators e.g. community networks in each of these villages can agree to peer to a regionalised rural IXP and therefore benefit from potential cost-savings both in terms of infrastructure (as it will now be shared) or in bandwidth (reduction in upstream link usage). Such an infrastructure has the potential to revolutionise the last-mile access in rural places.

Chapter 9

Conclusions and Future Work

This chapter concludes this doctoral thesis, by summarising the goals and the results as well as the main contributions from the studies exposed in the previous chapters. It highlights the key findings and ends with lessons learned and future work.

9.1 Contributions of this thesis

This thesis analyses Internet connectivity in Africa from various vantages points to understand the current limitations and identify a path forward. The main contribution of the thesis comes from its exposition of a severely under explored yet very crucial topic. The strength of thesis derives from its multifaceted exploration of the subject manner.

The thesis tackles the following facets of the problem: understanding the means of access and the network usage of underprivileged users in peri-urban South Africa, analysing the performance of local content access from various vantage points across Africa, evaluating alternative content delivery mechanisms, quantifying latency incurred due to routing peculiarities across the continent, and examining how IXP-related interventions can improve access to local content in Africa.

Furthermore, novelties in terms of both the findings as well as the developed methodology significantly improve over the current state of the art.

9.1.1 Internet usage in a township area in South Africa

Key Contribution 1

This chapter revealed how Internet usage of users in a low-resource environment are restrained by the lack of access, availability of services and data cost. It reinforced the concept of *locality of interest* and at the same time showing that the mainstream Internet services remain very popular. One main methodological contribution lies in the experience gained through the mixed-method strategy of using both quantitative and qualitative techniques applied for data collection, which will be applicable for larger-scale studies.

The aim of this first study was to shed some light on how Internet is being used and consumed in low-resource areas, particularly in two South African township communities. It first started with understanding mobile Internet usage in South African townships. In contrast to previous studies, which have studied mobile data usage in developing regions (including South Africa), the study focused on two townships in South Africa; the extremely resource-constrained nature of townships provided empirical evidence, for the first time, on how people in these communities use mobile data. A mixed-methods study was carried out, combining quantitative network measurements of mobile app usage with qualitative survey data to gain insights about mobile data usage patterns and the underlying reasons for user behaviour concerning mobile data usage. Due to the limited availability of public free Wi-Fi and despite the relatively high cost of mobile data, it was observed that a typical township user's median mobile data usage was significantly more than Wi-Fi usage. As expected, and consistent with observations of mobile data usage in parts of South Africa with better resources, users favoured using Wi-Fi (whenever available) for streaming video applications, such as YouTube. Interestingly, however, unlike users in less resource-constrained settings, township users also consumed significant mobile data to update mobile applications, as opposed to relying on Wi-Fi networks for application updates. This behaviour suggested that network and mobile application designers must pay more attention to data usage patterns on cellular networks to provide mobile-based services that provide more cost-effective mechanisms for tasks such as application update.

This first study was complemented with a network traffic characterisation of Internet usage, after deploying a community network in a peri-urban township of Cape Town, South Africa. The study looked at the first six months of Internet and localised services traffic based on data collected at two main locations (the school and the mesh). As such, the traffic profile, transfer sizes, and throughput were studied. Several trends in the time series data were identified, such as diurnal patterns, consistency (typical usage) from day to day, and heightened usage patterns on weekends. On many occasions, the reliability of the network was affected mainly due to links going down and load-shedding. Initial usage clearly indicated a demand for internet-based external services and to a lesser extent local services. It was concluded that the community network was often being used as a means of entertainment.

In the results, there were skewed distributions with high variability (e.g., transfer sizes, throughput), and heavy-tails (e.g., connection duration, transfer sizes). The use of localised services, though consistent, remained relatively low as compared to the use of Internet-related services. It was argued that growth in relevant local content (for e.g. locally produced music and videos) will help in promoting the usage of zero-rated local services, instead of using bandwidth-greedy applications such as YouTube. Additionally, the web traffic analysis has also shown that pattern, whereby, a lot of data is being consumed by background services such as anti-virus software, phone and PC updates. Users buying vouchers are actually unaware that a considerable amount of data is lost in software updates.

It was argued that the use of localised services comes with the availability of relevant content and demands more promotion from the local community. This therefore highlights the importance of local content hosting and the challenges to access local content, which were looked into in the following chapters.

9.1.2 Content hosting and distribution

Key Contribution 2

The case studies in this chapter revealed how a majority of Africa's local content is still hosted remotely and this has a major incident on the Quality of Experience (QoE) of users in Africa. The main contribution is the investigation of the use of local news and public service websites as proxy for local content.

By studying the Internet usage patterns in a typically low-resource setting in a township area in Africa, the thesis helped to understand the needs of the end-users for accessing and using the Internet, as a tool for education, business and entertainment. It was argued that promoting the development of local content and localised services is a key element in building a more resilient and robust Internet ecosystem. This chapter looked into two main challenges: (1) content hosting and (2) access to cloud-based services, both to support the provisioning of local content and services.

The first part of this study provided empirical evidence on the current configuration of web content hosting, access, and distribution in Africa, and demonstrated that the status of the African content infrastructure is inadequate. It was found that a large majority of African countries rely heavily on foreign services, both to host, to access, and to distribute local content in Africa. The thesis showed that latency levels to remotely hosted local content were high as well as costs of accessing remotely hosted local content. Additionally, it was argued that most of the public policy strategies on improving local content in Africa had mainly focused on demand-side interventions, such as the creation of content in local languages, and on developing skills on web content production and consumption. While these policies are important, bodies in charge of the governance of the Internet should identify ways of facilitating local markets for content hosting, access and distributions by focusing on: (1) incentivising investments on data centres and web farms in Africa, to stimulate economies of scale for the local web hosting market; (2) encouraging local news websites to move the content closer to the users in Africa, by fostering the use of CDN-enabled networks and by reducing prices for local hosting, (3) Facilitating peering relationships between ISPs and investing in local exchange points to reduce latency; and (4) encouraging ISPs to peer in local exchange points.

The second part of this study investigated the availability and performance of existing cloud services and cloud service providers focussing on the public sector as a use case. It showed that in some African countries, access to public sector websites is largely characterised by high Internet delays. In addition, a large proportion of public sector websites were being hosted remotely, i.e. in other countries. It was also observed that of the five countries surveyed, Nigeria and Ghana had the highest percentage of remote hosting and experienced the highest latencies. A large portion of the local news websites were hosted in USA (58%), Canada, EU (16%), and South Africa (14%). While the hosting networks generally have global operations, they did not necessarily have physical infrastructure in most of the African countries. This meant that while offering the convenience of cloud-based hosting, lack of physical infrastructure in Africa entailed that Africa's web content was stored in remote locations. Additionally, it was found that remote storage of web content could potentially have a negative implication on the sovereignty of African countries in that they lose control of their data. In addition, the burden of fetching content from remote locations falls on local network operators, the cost of which get passed on the users. This ultimately has negative implications on the local economies, and also in terms of poor quality of experience due to high latencies as reported in this study.

9.1.3 Alternative content delivery mechanisms

Key Contribution 3

This chapter showed the benefits but also the limitations of alternative means of content delivery and their applicability in the context of developing regions. The main contribution is reproducible methodology used for large scale studies performed on systems deployed in the wild.

After diving into the challenges of content delivery and content hosting in Africa, this thesis performed an in-depth analysis of two different initiatives (1) Free Basics: a "zero-rated" service from Facebook and (2) Accelerated Mobile Pages (AMP): a mobile optimisation technology by Google. Both platforms have very similar objectives, albeit using different technologies, which are to reduce the cost of access to local content and increase the Quality of Experience (QoE) of the end-user - especially targeting users in low-income areas.

Free Basics is an initiative backed by Facebook to provide users in developing countries *free* mobile Internet access to selected services. It has already been deployed in over 35 heavily populated countries in Africa, Asia, Central- & South America and if successful, could go a long way towards bridging the digital divide. Despite its widespread deployment and its potential impact on bridging the digital divide, to date, few studies have rigorously measured the quality of the free Internet service offered by Free Basics. This study characterised the quality of the Free Basics service offered in Pakistan and South Africa along three dimensions: (i) the selection of accessible Web services, (ii) the functionality of those services, and (iii) the network performance for those services. It highlighted the low quality of network access (compared to paid network access) offered by Free Basics to a walled garden of stripped-down services. Free Basics services can see 4-12 times slower network performance than their paid counterparts and there are multiple factors contributing to this performance gap. This implies that the net neutrality debate should be more nuanced than the "free gets advantage" arguments, asking additional questions like "free, but with what constraints?".

A second point of concern against the Free Basics program is the unfair advantage free web services have over their paid counterparts, violating net neutrality. Thus though Free Basics services are at an advantage due to zero rating, the network QoS each service gets depends on Facebook-imposed and the cellular-provider-imposed limits (another potential net neutrality violation). Further, different clients can see different performance for the same service, depending on which cellular provider they use.

The second part of the study focused on the performance impact of Google's AMP in Africa as an alternative mechanism for content delivery. As opposed to Free Basics, which is a zero-rated service, Google AMP focuses on optimising web and mobile performance by applying various web content compression and caching techniques. The study analysed the hosting situation of 1191 African news websites, focusing on such metrics as RTTs and number of hop between African vantage points and the websites, hosting countries and networks, pages sizes, and page load times. This thesis further performs an analysis on 194 of the 1191 websites that were found to be using the AMP infrastructure by comparing access via AMP and traditional web hosting. The results indicated a significant reduction in website sizes as downloaded onto web clients by a factor of 8. This reduction creates significant savings in data costs for Internet users in Africa, especially for mobile Internet users. In terms of performance, the results indicated that page load times are much higher in Africa compared to EU and US (50% of website load times in Africa are over 15s, compared to EU/US where 70% of pages load under 15s), but significantly lower using AMP (80% lower than 10sec). When AMP is used, there was a significant improvement in page load, with over 80% of the pages loading under 10s.

While AMP's performance improvements in Africa are obvious, there have been deep concerns about Google's dominance in online search. Just as with Free Basics, Google AMP constrains users to remain within the Google ecosystem, meaning that instead of sending the end-users to the content publisher's website (and allowing the publisher to generate meaningful information about their reader base), the end-user remains within the Google precinct. This poses a huge problem of net neutrality and data privacy.

The findings from studying both Free Basics and AMP show that such data-driven studies are essential for having more informed public debates on the pros and cons of the current design of the Free Basics service as an initiative to bridge the digital divide. Further discussion needs to be had in terms of how the platform promotes externalisation of Africa's local content. The findings in this thesis, would allow to better understand the current underpinning of local content generation and consumption in developing regions.

9.1.4 Latency in African networks

Key Contribution 4

This chapter revealed the uneven landscape of Internet performance in Africa and provided evidence about the lack of cross-border connectivity between many neighbouring countries. A practical contribution has been the framework used to analyse the data in order to gain an understanding of the interconnection landscape between African countries.

An important enabler for the growth of local content hosting and distribution or the delivery of localised services in the cloud is the underlying QoS (Quality of Service). If African network operators want to promote local content hosting between and within Africa, they need to make sure latency within and between African countries remains reasonably low. The aim of this chapter was to give some insight into the impact of cross-border infrastructure and logical interconnections in Africa by comparing Internet performance measurements between different countries.

It focused on mapping the performance and topological characteristics of *intra*-Africa connectivity. The results discovered a series of "communities", in which countries have built up low delay interconnectivity, dispelling the myth that intra-delays in Africa are universally poor. Unfortunately, this does not extend to the remainder of the continent, which typically suffers from excessively high inter-country delays, often exceeding 300ms. To explain this, intra-continental topology was explored to discover a number of shortcomings, most notably an excessive reliance on international transit providers rather than local peering.

A dataset of ICMP pings between countries was gathered using a software probe platform and applied a community detection algorithm to group countries based on round trip times (RTTs) between themselves. Three main latency clusters could be observed as being East and Southern Africa, North Africa, and West and part of Central Africa. An interesting observation is that these clusters largely correspond to countries sharing the same official languages or past colonial history. Of the three clusters, Eastern and Southern Africa appear to be the most "strongly clustered", as they have the lowest inter-country latency values as compared to the rest of the other two clusters. It was also found that some countries have a much higher intra-country latency than expected, pointing to the lack of local peering or physical infrastructure within the country itself. This highlights the importance of physical networking infrastructure deployment and inter-network relationships at a regional level. The study found that many intra-country delays in Africa have reached relatively developed levels and a large set of intra-country samples were below 40ms (*e.g.,* Benin, Egypt, South Africa), and below 30ms (Ivory Coast, Réunion, Mauritius). Furthermore, a series of country clusters was identified, which have also built up strong inter-connectivity.

The findings have shown that performance varies heavily based on region: Whereas some clusters have relatively low levels of delay (*e.g.,* the median intra-cluster delay in the South is just 46ms), other areas have consistently high delay. For example, the Western African cluster suffers from intra-cluster delays that are similar to its inter-cluster delays. The analysis confirmed that this is largely driven by the use of transit providers that route traffic through Europe and North America. By offering an effective means for automatically extracting regions and networks that critically require more local peering and interconnection, the areas of interventions both from a technical and policy perspective can be determined. Only by addressing these issues will it become possible for high-performance service hosting and interaction across the entire African continent.

9.1.5 Importance of localised Internet infrastructure

Key Contribution 5

This chapter proposed a model for assessing the readiness of the local infrastructure of a country and provides a statistical model to evaluate the impact of IXPs on local content development. Understanding the nature of the relationship between local content activity and the growth of IXPs is a key empirical contribution of this chapter.

With increasing demand for better quality of service, network operators are constantly looking for better interconnection arrangements to optimise both content delivery to the edge and manage their costs to remain competitive. The last chapter discussed the importance of localising Internet infrastructure, namely Internet Exchange Points (IXPs) as a means to improve access to local content. It highlighted the benefits of a local peering infrastructure which are: reduced usage of international connectivity, a more resilient in-country network, lower latency and at the same time providing a platform for better technical coordination.

Using a simple multi-level maturity model, this study categorised the readiness of African countries to provide a localised Internet infrastructure. Out of the 54 African countries, 20 countries did not have an IXP yet (Level 1). It was found that most of these countries are lagging in terms of Internet penetration and affordability, usually operating a monopolistic telecommunication structure. 11 countries are operating at Level 2, which means that they have managed to establish an IXP and connects more than three local networks. IXPs operating at this "swing" stage have their own sets of challenges e.g. to share operational costs of running an IXP and to make it attractive to both local and international players. Having a proper governance model is key to the success of an IXP at this stage. 10 IXPs are operating at Level 3, which means that they managed to grow and attract CDNs and other edge caches to operate alongside the IXP. This means there is some amount of collaboration between the local networks to share the costs e.g. bandwidth for cache-fill. Finally, 8 IXPs are in the most advances stages (Level 4 and 5) with the presence of carrier-neutral data centres. This in turn attracts both regional and international carriers to set up PoPs at these IXPs transforming them into regional hubs for traffic exchange.

Using multiple datasets, this research gathered important metrics quantifying the factors that could impact the development of IXPs and consequently, the development and consumption of local content. The thesis modelled the relationship between different variables, using a fixed-effects statistical framework, and estimated the effects of the growth of IXPs and the *local content activity*. It was found that the scale of an IXP (in terms of the number of peers) is positively correlated and statistically significant with *local content activity*, which is a function of the number of domains of a country's ccTLD and the number of web pages indexed by Google. The result was that a 10% growth of the scale of an IXP there is a 2.18% increase in the *local content activity* of a country.

Despite the benefits of IXPs, there are many obstacles to the establishment and smooth operation of local peering platforms. It is usually more difficult to establish an IXP in a country where there is still a dominant incumbent operator. It has been observed that in markets where the dominant operators has more than a 50% market share and they usually do not encourage the growth of an IXP, out of fear of losing transit customers. Collaboration and trust between local and international stakeholders is key to create an enabling environment. To further understand these implications, the thesis looked into two success stories in Africa (IXPs in Kenya and Nigeria), which provided very important lessons on how a conducive environment, backed by a proper regulatory environment, can unlock regional interconnection opportunities and hence provide a better quality and more affordable access to end-users in developing countries.

9.2 Future Work

Addressing the barriers to Internet access in developing countries is possible and necessary. Despite of the plethora of benefits related to Internet access, penetration in developing countries remains appallingly low. High costs and poor connectivity limits Internet penetration and the success of Information and Communication Technologies (ICT). Unfortunately, affordable Internet access often requires the combined efforts of multiple co-dependent agents (e.g. network operators, content providers, cellular providers, regulators). The case of Africa is particularly striking. Amongst the many problems observed in the region, this thesis provided empirical evidence of the phenomena of "tromboning", whereby two neighbouring networks may have to transit their traffic via distant locations (chiefly Amsterdam, London and Frankfurt) to reach each other. In conjunction with this lack of regional network infrastructure, African Internet users mostly consume content and services from abroad (e.g., US and Europe). As seen in this thesis, such practices have been found to be highly detrimental to end user experience and network operator costs. This results in a poor quality of service and high costs for Internet provision: a vicious circle in which no single agent has sufficient incentives (or individual capacity) to break. For example, because local demand is low, Content Distribution Networks (CDNs), have little economic incentives to provide servers and storage in Africa. Yet the resulting poor quality of service means that demand is subsequently difficult to encourage. These observations are mirrored across many global and regional stakeholders. In fact, even African web operators tend to host their content abroad rather than within their own country. Improving last mile connectivity alone will not ameliorate these problems.

Only by integrating the efforts of these disparate stakeholders the Internet access/provision challenges in Africa can be addressed. Future research should directly find innovative solutions to: (1) Address the suboptimal topological characteristics of the African Internet to support local network operators in identifying and ameliorating inter-continental tromboning; (2) Address the underlying reasons behind poor content and service provisioning in Africa; (3) Identify the presence of economic incentives for maintaining the status quo and impeding innovations in interconnection practices and (4) Support the establishment of key new infrastructure via a data-driven recommendation strategy that identifies deficiencies and solutions in regions. Critically, future work will integrate socio-economic and technical considerations to underpin these three strategies, such that it can translate these recommendations into appropriately incentivised actions that are communicated directly to relevant stakeholders (who are called the "change-makers"). Through this, breaking the deadlock is possible.

The actions should focus on mapping, measuring, surveying and understanding the combined technical and economic issues/incentives that affect both Internet supply and demand in Africa. This can be achieved by developing novel measurement techniques and platforms which will encompass the collection and analysis of never-seen-before data streams. The outcome of this process will be a series of targeted and incentivised solutions that can be deployed by Internet stakeholders in the region. Below is a series of concrete actions proposed as a way forward:

1. Deploy a live Internet measurement platform in Africa that will collect and collate high fidelity Internet-related data for analysis by regional stakeholders.

2. Collect pan-African socio-economic data on a country-specific basis, such that it can be integrated with relevant technical data from the same localities.

3. Develop tools to automatically identify major technical and socio-economic bottlenecks facing expanding Internet penetration in Africa, as well as improved Quality of Service and reduced operating costs.

4. Compose and evaluate properly incentivised solutions for individual stakeholders wishing to improve their operations and lower costs.

9.3 Lessons learned

9.3.1 "Africa is not a country"

This thesis has shown that Africa is made up of "islands of connectivity" ranging from hyper-connected regions with high density fibre network, while other regions are characterised by vast spaces of land where there is no network coverage. Land-locked countries have a different telecommunication landscape as opposed to sea-borne countries. They need to rely on important cross-border arrangements for international connectivity which sometimes are problematic because of political tensions.

As such, there has been a lot of misconceptions around the African Internet and how it is evolving. Africa has always been portrayed as the least developed continent with infrastructure that is still lagging behind. This thesis contributes towards demystifying these claims and show how diverse the continent is in terms of connectivity. This thesis shows that Africa is just a geographical term that simply does not translate to the Internet coordinates and talking about "Africa" in the network connectivity context in not accurate.

9.3.2 The need for technical Internet data in Africa

As seen in this thesis, the African Internet faces many poorly understood challenges. Despite using identical protocols, the deployment decisions made by African stakeholders means that Internet operations are very different to their Western counterparts. For example, the lack of interconnection between networks and the paucity of content/application servers in the region mean that recent trends (e.g. cloud computing, remote hosting) have actually undermined the growth of local African operations, pushing services outside of the continent to be hosted in the US or EU. This deficiency makes it difficult to formulate evidence-based solutions, or evaluate the success of newly deployed technologies and investment schemes (e.g. the African Union's PIDA).

Due to the above, pan-African organisations such as AFRINIC and the African Union have recognised the need for greater data-driven activities. A good example has been the AXIS project[1], a major initiative to expand the use of IXPs, identified data collection as a key need. Despite this, data collection is limited to basic statistics, and it still fails to be exploited in more impactful ways, e.g. extracting insight on optimal peering, potential routing problems, security risks or the need for particular third-party content hosts. It is vital that technical data collection across Africa becomes current practice, and that it is appropriately analysed to discover bottlenecks facing the expansion and improvement of operations within and between networks.

To achieve the above, AFRINIC and other regional organisations should join hands to build a robust Internet measurement network made of custom and existing tools such as RIPE Atlas probes, M-Lab/Speedtest clients and servers. It is important to piggyback on existing infrastructure in order not to re-invent the wheel.

9.3.3 The need for socio-economic Internet data

The need for socio-economic Internet data on technical deficiencies in Africa are only a subset of the problem space. In many cases, sub-optimality is also driven by a lack of market incentives, combined with many other complex socio-economic barriers. Understanding these barriers is vital for formulating practical solutions that reflect and address regional and local needs. This applies both to the identification of

[1] https://au.int/en/african-internet-exchange-system-axis-project-overview

bottlenecks (many of which are of a socio-economic nature, e.g. affordability, digital and traditional literacy, being off-grid, gender-discrimination, market factors) and to the design of sustainable solutions (which will largely rely on economic incentives for uptake).

In essence, each stakeholder within the value chain (i.e. users, network operators, content/service providers, umbrella organisations, local communities and policymakers) must be understood in terms of its resources and needs. Unfortunately, such stakeholder's specific socio-economic data is notoriously hard to gain in a reliable manner and secondary sources (e.g. Internet subscription prices) often fundamentally lack the required depth to provide useful insights. For example, a true understanding of affordability requires measuring the objective and subjective obstacles impacting individual supply and demand, as well as dependent factors such as gender discrimination, generational divides, illiteracy, social constraints and income sources.

Similarly, measuring the market forces that drive competition amongst Internet Service Providers (ISPs) must look beyond pricing to include concerns such as accessibility, value-add services as well as the legacy of state-owned operations. Existing secondary sources, such as the Word Economic Forum Network Readiness Index[2] or the Web Index[3], while being of critical relevance in directing policies intervention, still lack the details and level of penetration required for a fuller understanding of existing digital divides become quickly out of date by the time they are published. Similarly national surveys, while essential in providing a broad socio-economic and demographic picture of the country (on a ten-year interval), often have a very limited focus on ICT and internet affordability and availability, and is also unable to capture changes in the dynamic mobile internet market that is driving broadband demand. Hence, to overcome this hurdle, it is necessary to perform large-scale bespoke survey and interview campaigns targeted at Internet usage.

9.4 Concluding remarks

This thesis unveils the complexities of content delivery in low-resource networks and proposes a series of policy recommendations to improve Internet access in developing regions. As the world is going through this global pandemic of the COVID-19, with lock-downs, social distancing, teleworking and homeschooling becoming the "new normal", our reliance on the Internet has increased tremendously. The way we do

[2]https://networkreadinessindex.org/
[3]https://thewebindex.org/

business, interact with friends and families has changed and the Internet has become an indispensable tool, enabling communities and businesses to stay afloat amidst the crisis. In most part of the world, the Internet infrastructure has performed well and sustained the global increase in traffic of 47% in 2020 (instead of the forecast of 28%) [203]. However, people living in under-provisioned areas do not benefit from the same level of resilience, yet they faced the dire consequences of the pandemic.

In the face of such adverse situations, governments and regulators should take appropriate actions to protect the most vulnerable and provide basic access to Internet services. To build a more resilience and inclusive Internet ecosystem, governments should *inter alia* promote open access policies such as dig-once regulations and spectrum sharing. Further, promoting a free and auto-regulated market would trigger sound competition and bring the cost of connectivity down. No one should be left behind and special policies should be put in place to bring onboard excluded populations living in remote areas, for example through "Universal Service Funding" mechanisms.

Moreover, an increasingly alarming problem is state-sponsored Internet disruption. African countries are not being spared from arbitrary Internet shutdowns as it has been the case for Ethiopia, Uganda or Zimbabwe in 2020[4]. Proper legislation and regulatory frameworks should be setup to reduce government interference and control over Internet Service Providers (ISPs). Governments should also make additional efforts to protect the fundamental rights to privacy and freedom of expression without interference (Article 19 of the Universal Declaration of Human Rights).

To conclude, it is important to quote what Sir Tim Berners-Lee said during the launch of the *Contract for the Web* [204] in 2018: "The power of the web to transform people's lives, enrich society and reduce inequality is one of the defining opportunities of our time. But if we don't act now — and act together — to prevent the web being misused by those who want to exploit, divide and undermine, we are at risk of squandering that potential".

[4] https://www.bbc.com/news/world-africa-47734843

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Appendix A

Appendix

A.1 Mobile Data Usage Survey

Mobile data usage survey

This research is being conducted by Dr. David Johnson and Amreesh Phokeer at the University of Cape Town. The purpose of this research project is to understand how participants use their mobile phones in terms of applications and data usage. This survey is completely anonymous, no personal data will be requested.

* Required

Email/Name

Your answer

Select a location *

- ○ Masiphumelele
- ○ Ocean View
- ○ Red Hill
- ○ Khayelitsha
- ○ Other:

Select the category in which you are: *

- ○ School student
- ○ School staff
- ○ NGO staff
- ○ Self-employed
- ○ Employed
- ○ Other:

What type of mobile device do you have access to? *

- ☐ Feature phone (Basic phone)
- ☐ Smartphone (Android/IPhone)
- ☐ Tablet
- ☐ Netbook/Laptop
- ☐ Wearable gadgets
- ☐ Other:

How many devices do you have connected to the Internet? *

Choose

What is the OS of your device? *

- ☐ Android
- ☐ IOS
- ☐ Blackberry
- ☐ Windows
- ☐ I have a feature phone
- ☐ Other:

You connect to the Internet using: *

- ☐ Cellular (2G/3G/4G LTE) Pay-as-you-go
- ☐ Home broadband
- ☐ Free public wifi (Isizwe, Isabelo, shopping mall, restaurants, etc)
- ☐ Paid connection at Internet Cafes
- ☐ Free wifi at work/school library
- ☐ Other:

Which of the following mobile providers are you subscribed to *

- ☐ Vodacom
- ☐ MTN
- ☐ Cell-C
- ☐ Telkom
- ☐ Virgin
- ☐ Other
- ☐ I don't have a mobile subscription

What type of broadband Internet connection do you have at home?

- ○ I don't have home broadband
- ○ Capped broadband (weekly or monthly limited data plan)
- ○ Uncapped broadband (no limit)
- ○ Prepaid broadband
- ○ Other:

What type of data bundle do you have on your mobile? *

- ○ Capped data plan
- ○ Uncapped data plan
- ○ Just airtime (no data bundle)

How often do you have wi-fi access during the day? *

- ○ Most of the day
- ○ A few times a day
- ○ Never
- ○ Unsure/I don't know

What educational information or resources do you access using your mobile phone?

- ☐ Online libraries
- ☐ Youtube videos
- ☐ Khan academy
- ☐ Wikipedia
- ☐ Other:

What are the applications you use on the Internet *

- [ ] Whatsapp/Viber
- [ ] Facebook
- [ ] Youtube
- [ ] Gmail
- [ ] Shareit
- [ ] Games
- [ ] Opera Mini
- [ ] Other:

Each time you connect to the Internet, approximately how much time you spend per session? *

- ○ Less than 15 min
- ○ At least 15 min
- ○ At least 30 min
- ○ At least an hour
- ○ More than 1 hour
- ○ I am always connected
- ○ Other:

How often do you access Internet from your device? *

- ○ A few times a day
- ○ A few times a week
- ○ A few times a month
- ○ I barely use my phone for Internet
- ○ Other:

What are the main activities do you carry on the Internet using your mobile phone? *

- [ ] Socialising
- [ ] Communication
- [ ] Accessing educational content
- [ ] News
- [ ] Entertainment (Music, Games)

Which of the following services you spend the most amount of money on? *

- ○ Phone calls
- ○ SMS
- ○ Mobile data
- ○ I don't know

Tell us whether you agree or disagree with those statements? *

	Agree	Slightly Agree	Neither agree or disagree	Slightly Disagree	Disagree
Mobile data coverage is good	○	○	○	○	○
Mobile data service is reliable	○	○	○	○	○
I would consider paying more for better speed	○	○	○	○	○
I'm satisfied with my current mobile data	○	○	○	○	○
I have trouble keeping track of mobile data costs	○	○	○	○	○
Mobile data Internet is affordable	○	○	○	○	○

What are the main reasons you would not use Internet on your mobile?

- ○ I prefer to use other devices (more comfortable)
- ○ My device is not compatible
- ○ I don't know how to use it
- ○ It's too expensive
- ○ Other:

Do you use any of those services

- [ ] Freebasics on Cell-C
- [ ] MTN Free Wikipedia Access and Momaths
- [ ] Vodacom e-school
- [ ] Telkom ShowMax VoD
- [ ] Free Whatsapp Messaging on Cell-C
- [ ] Other:

How much money do you spend in a month on mobile data? *

Choose ▾

Do you think mobile data is:

- ○ Very cheap
- ○ Rather cheap
- ○ Expensive
- ○ Very expensive
- ○ Not affordable

How many friends do you have on social media?

Choose ▾

Most of your social media friends are between:

- 0 to 10km (same locality)
- 10 to 30km (In the neighbouring places)
- > 30 km (far away)
- Other:

What proportion of your social media friends do you meet physically?

- Most of them
- Some of them
- A very few of them
- None

How often do you meet your social media friends physically?

- Quite often
- Very often
- Sometimes
- Rarely
- Never

How often do you travel from your locality to another? *

- Everyday
- 1 or 2 times a week
- 1 or 2 times a month
- Never

How often do you use your mobile Internet when you are away from home? *

- All the time
- Occasionally
- Rarely
- Never

Which of the following would you do if you have free mobile Internet? 1-Not really 5-Mostly *

	1	2	3	4	5
Browsing the web	○	○	○	○	○
Watching online videos	○	○	○	○	○
Voice over IP (Whatsapp, skype)	○	○	○	○	○
Video conferencing	○	○	○	○	○
Messaging	○	○	○	○	○
Social media	○	○	○	○	○

Researcher notes (to be filled by researcher only)

Your answer

Submit

A.2 Survey results

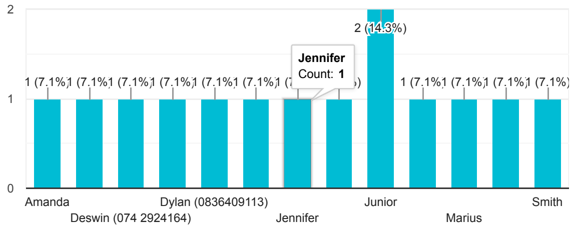
Mobile data usage survey

14 responses

Publish analytics

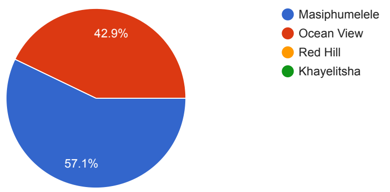
Email/Name

14 responses



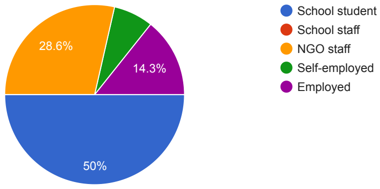
Select a location

14 responses



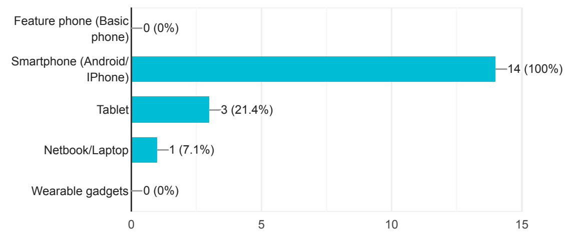
Select the category in which you are:

14 responses



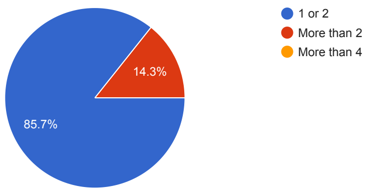
What type of mobile device do you have access to?

14 responses



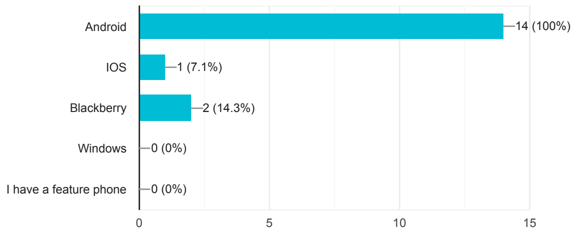
How many devices do you have connected to the Internet?

14 responses



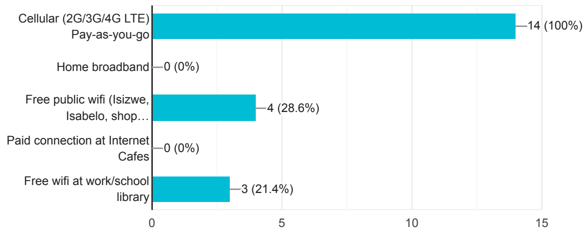
What is the OS of your device?

14 responses



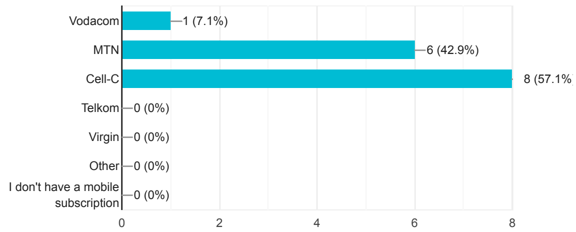
You connect to the Internet using:

14 responses



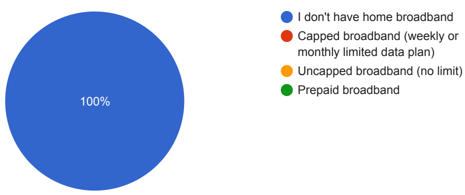
Which of the following mobile providers are you subscribed to

14 responses



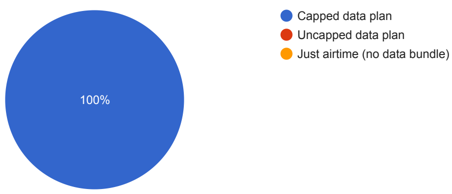
What type of broadband Internet connection do you have at home?

14 responses



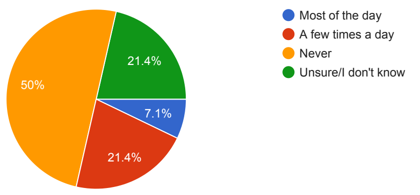
What type of data bundle do you have on your mobile?

14 responses



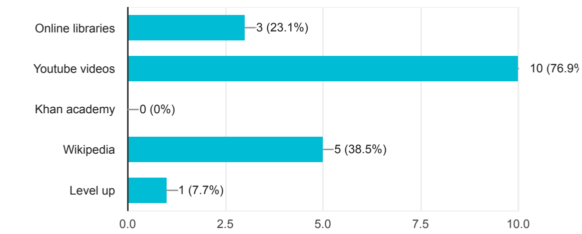
How often do you have wi-fi access during the day?

14 responses



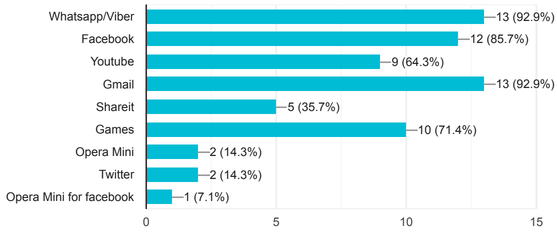
What educational information or resources do you access using your mobile phone?

13 responses



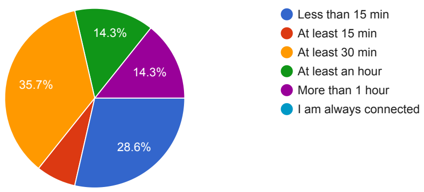
What are the applications you use on the Internet

14 responses



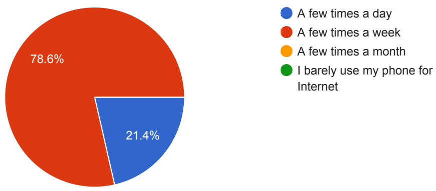
Each time you connect to the Internet, approximately how much time you spend per session?

14 responses



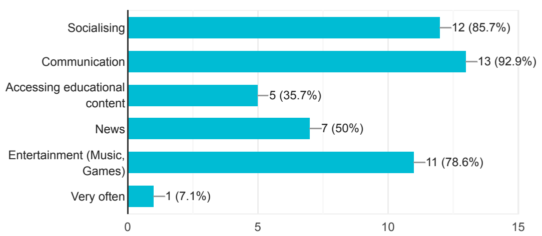
How often do you access Internet from your device?

14 responses



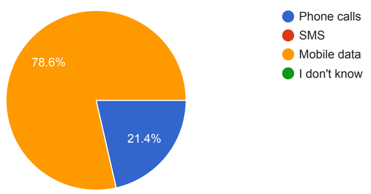
What are the main activities do you carry on the Internet using your mobile phone?

14 responses

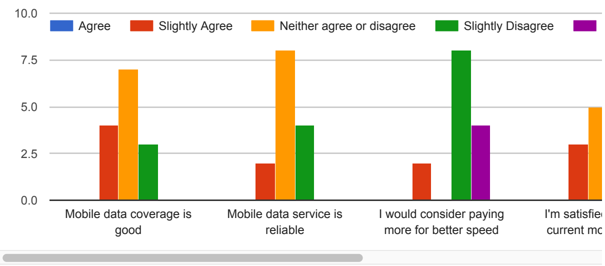


Which of the following services you spend the most amount of money on?

14 responses

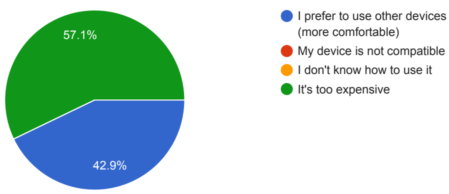


Tell us whether you agree or disagree with those statements?



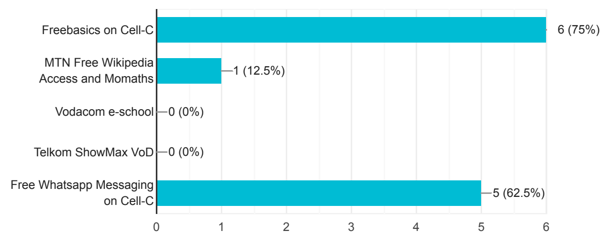
What are the main reasons you would not use Internet on your mobile?

14 responses



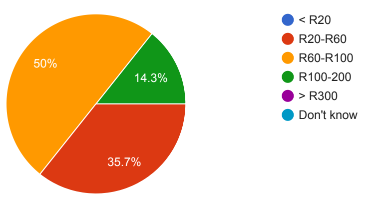
Do you use any of those services

8 responses



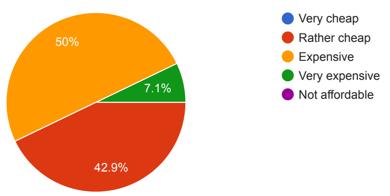
How much money do you spend in a month on mobile data?

14 responses



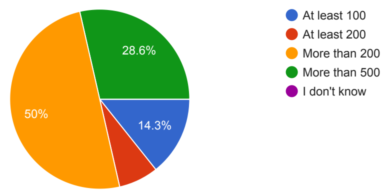
Do you think mobile data is:

14 responses



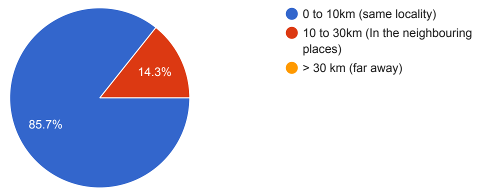
How many friends do you have on social media?

14 responses



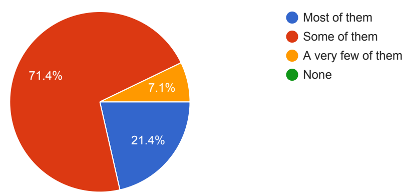
Most of your social media friends are between:

14 responses



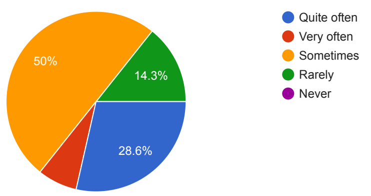
What proportion of your social media friends do you meet physically?

14 responses



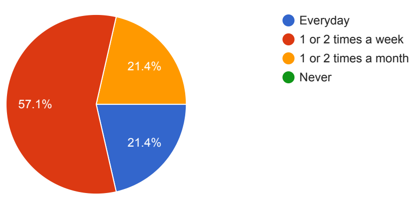
How often do you meet your social media friends physically?

14 responses



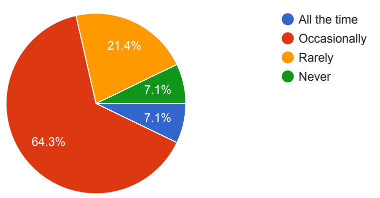
How often do you travel from your locality to another?

14 responses

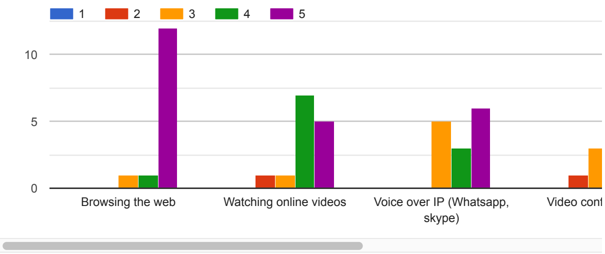


How often do you use your mobile Internet when you are away from home?

14 responses



Which of the following would you do if you have free mobile Internet? 1-Not really 5-Mostly



Researcher notes (to be filled by researcher only)

6 responses

I spend sometimes R5 or R10 each time I recharge and I can recharge up to 5 times per week. I buy the R5 monthly Whatsapp bundle on Cell-c but I cannot do whatsapp calling, only messages, images etc. I sometimes use freebasics but I don't like to use facebook on this as no videos/images available. I have more than 1000 friends on facebook, some of them living in neighboring townships but most of them live in Masiphumelele. If Internet was unlimited, I would look for more information on school subjects, see how I can download new applications, videos. I can use data-intensive apps such as skype or google maps to locate things, while moving around. Learn new things by watching online videos.

I use R5 and R10 and when it is over, I go and recharge. I don't really keep track of how much I spent, but I can recharge like up to 5 times a week. I use the Cell-C whatsapp bundle because it's cheap R5 for a month, but I cannot use it for calling only messaging. I sometimes use freebasics but I find it very slow and facebook doesn't have images and videos. If Internet was free, I would look for school related information much more, how to download videos and music but also use data-intensive apps such as Google maps. I can also learn new things by following online tutorial on Youtube. Doing Skype right now is also too expensive, this is something I would like to do, and I would keep my phone always up-to-date with latest patches.