Four Years Tracking Unrevealed Topological Changes in the African Interdomain

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Abstract

Despite extensive studies on the Internet topology, little is still known about the AS level topology of the African Internet, especially when it comes to its IXP substrate. The main reason for this is the lack of vantage points that are needed to obtain the proper information. From 2013 to 2016, we enhanced the RIPE Atlas measurement infrastructure in the region to shed light on both IPv4 and IPv6 topologies interconnecting local ISPs. We increased the number of vantage points in Africa by 278.3% and carried out measurements between them at random periods. To infer results that depict the behavior of ISPs in the region, we propose reproducible traceroute data analysis techniques suitable for the treatment of any set of similar measurements. We first reveal a large variety of ISP transit habits and their dependence on socio-economic factors. We then compare QoS within African countries, European countries, and the US to find that West African networks in particular need to promote investments in fiber networks and to implement traffic engineering techniques. Our results indicate the remaining dominance of ISPs based outside Africa for the provision of intra-continental paths, but also shed light on traffic localization efforts. We map, in our traceroute data, 62.2% of the IXPs in Africa and infer their respective peers. Finally, we highlight the launch of new IXPs and quantify their impacts on end-to-end connectivity. The study clearly demonstrates that to better assess interdomain routing in a continent, it is necessary to perform measurements from a diversified range of vantage points.

Keywords: African Internet, IXP substrate, RIPE Atlas, transit, traffic localization

1. Introduction

An African Union-supported study from 2008 showed that Africa spends between $400 and $600 million per year in transit fees for intra-African traffic that gets routed through expensive transit links [5], and these fees have been increasing over time [36]. Initiatives such as the African Internet eXchange System (AXIS) were thus launched by the Internet Society (ISOC) to promote the creation of IXPs and enable cross-border interconnection [6], after a preliminary study [39] had reported that Internet eXchange Points (IXPs) would help improve Quality of Service (QoS) for local traffic. Meanwhile, large Content Delivery Networks (CDNs), in particular Google and Akamai, have started to deploy infrastructure in the region, driven by growing usage and the need to improve their user experience [25].

In addition, the African optical fiber infrastructure has seen major investments over the last decade, mainly motivated by the excessive cost and low QoS of satellite communications, and the demands coming from rapid expansion of mobile communications [72, 69, 67]. Despite this surge in investments, the terrestrial fiber remains fragmented [68] and there is still a considerable gap in the quality of Internet service when compared with developed regions [57, 25].

To examine the interdomain routing in Africa, recent work [28, 19, 30] relied on a very limited set of well-connected vantage points, and had different focuses, as explained in §2. By contrast, the key contribution of this paper is to obtain an interdomain map that covers the entire continent and is not biased towards a particular country or sub-region. To achieve this, we met and convinced ISPs in 31 African countries (out of 54), to deploy RIPE Atlas probes [63] within their networks. Our common efforts led to the deployment of 148 RIPE Atlas probes in 69 African ASes located in 31 countries giving a 278.3% rise in the number of vantage points in the region. We complemented our set of deployed probes with those already present in the region. For obtaining relevant topological data on access-to-access interconnection and tracking the evolution of traffic localization, our measurement campaigns monitored IPv4 and IPv6 end-to-end paths be-

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tween RIPE Atlas probes scattered throughout Africa at random periods over the last four years. We propose different techniques to analyze the data and infer results that depict ISP behavior in the region. Those techniques can be used to treat any set of similar measurements.

This paper continues the previous study [23], highlighting the evolution of the IXP substrate in Africa, analyzing and reporting on more measurements performed among local networks, focusing on the detection in our dataset of the usage of, or the launch of IXPs, and comparing performance experienced within African countries to those of European countries and the United States (US).

Our results illustrate that, with the exception of ISPs based in South Africa (ZA), the provision of intra-continental paths is dominated by ISPs based outside Africa, while South Africa is being adopted as a hub for East-West African communications (§5.3.1). We discover a large variety of ISP transit habits, notably correlated with the location, the official language, and the monetary union of the country in which the ISPs operate (§5.3.2). We further study the impact of such aspects on the AS path lengths (§5.2) and end-to-end delays between ISPs (§5.4), notably among networks based in the same country. We also expose the benefits of new IXPs with respect to end-to-end delay (§5.6.2).

We then define, in §5.5, the ratio *minimum measured RTT* to *best possible RTT among probes*, as a metric to evaluate QoS within the US, European countries, and countries in African sub-regions[1]. In this regard, we find that for West Africa, contrary to other regions, the interquartile range of measured RTTs is significantly higher than that of theoretical RTTs. The results indicate that West African networks in particular need to intensify terrestrial fiber deployment efforts and implement traffic engineering techniques to considerably reduce the aforementioned ratio.

Using two methodologies based either on the detection of known IXP prefixes in the traceroute data or on the evolution of AS path lengths and RTTs among local ASes over time (§4.2), we map 23 of the 37 African IXPs and improve previous studies that were not able to infer existing IXPs in the region [11]. As opposed to [30] which indicates that, by and large, local ISPs are not present and do not peer at local IXPs, we highlight how many local ISPs are found to peer at African IXPs in our dataset (§5.6). Next, we evaluate how frequent it is for IXPs from other regions to be traversed by intra-African communications (§5.6.3) to reveal that further efforts need to focus on increasing the number of local members at African IXPs so that peering is intensified in the region.

The rest of the article is structured as follows. In §2, we discuss related work. In §3, we describe the African interconnection landscape and present our motivations for this work. In §4, we present an overview of the data collection and sanity check. In §5, we present and analyze our results, which we further discuss and compare to previous work before concluding in §6.

[1] In referring to African sub-regions, we adopt the approach defined by the African Union [78, 4] to divide the continent into geographic regions.

2. Related work

Internet topology discovery, both at the router level and the Autonomous System (AS) level, is a topic that has been investigated extensively [27, 74, 46, 45, 31].

Bajpai *et al.* [12] provided a taxonomy of existing measurement platforms. They extensively described these platforms by exploring their coverage, scale, lifetime, deployed metrics, as well as measurement tools, architecture, and their overall research impact. One of the pioneers, CAIDA, has a long history of running Internet measurement platforms. Its latest active measurement platform, Archipelago, aims at reducing the efforts needed to develop and deploy sophisticated large-scale measurements [33]. For this article, a larger deployed base of vantage points in African networks was needed, so Archipelago was not used. The PingER project [58, 79] aims at measuring Internet end-to-end performance and was notably used to quantify the digital divide. At the beginning of this work, its infrastructure contained 89 monitors and 1090 remote monitored nodes at 956 sites in 169 countries. Although it involves 46 African countries, only Burkina Faso and South Africa host a monitoring site, which prevented us from doing large scale end-to-end measurements. Spring *et al.* [70] used Rocketfuel to analyze Routeviews BGP table dumps combined with traceroutes performed by 750 vantage points targeting 10 ISPs in the US. A key aspect of this work is the targeted analysis of a restricted set of ISPs instead of an attempt to map the whole Internet. We follow the same focused approach, targeting African ISPs.

In [28], Gilmore *et al.* mapped both the router and AS level graph of intra-African Internet paths. For a week, traceroutes were performed from a source in South Africa (ZA) towards many randomly selected IP addresses in all IP ranges allocated by AFRINIC. Their results were enhanced by AS adjacency data extracted from BGP-speaking routers in the ZA Tertiary Education Network. This resulted in one-way paths from which a tree was inferred, with ZA at the root. They acknowledged that the link density might look different if the traceroute probes were sent out from other countries in Africa. In 2009, Augustin *et al.* used diverse techniques to map IXPs in the Internet [11]. They successfully detected 223 of the 278 IXPs with known prefixes located all around the world. Unfortunately, their attempts to infer IXPs in Africa were often unsuccessful. This can be explained by the existence of only four looking glasses on the continent. Also, African IXPs sometimes utilize RFC1918 address space, which may have prevented the use of various detection techniques. The authors acknowledged that they lack sufficient information to infer the presence of these IXPs that are known to exist and be active.

To investigate Internet connectivity in Africa, Gupta *et al.* performed traceroutes from access networks in Tunisia (TN), Kenya (KE), and ZA [30] to sites hosting popular content. They noticed that 66.8% of the paths going from their vantage points towards Google cache servers located in Africa leave the continent. Since broadband access networks in those three countries are more developed [19] than in most of the 51 remaining African countries, the results of this study may not reflect connectivity in other countries, as acknowledged by the authors. Recently, Chavula *et al.* [18] examined communications among African research networks. They launched traceroutes from five African Ark monitors in residential/university networks to 95 university locations in 29 African countries. The measurements were performed for 14 days (April 6 – 20, 2014). They found that 75% of the paths are routed via Europe (EU) and the US. The percentage of intercontinental paths from their vantage points was evaluated to 95% in West Africa, 70% in Central Africa, and 60% in Southern Africa. They observed that RTTs are therefore affected by an increase of 150ms on average. Hence, they suggested the use of Software Defined Networks in IXPs, multi-path traffic engineering, and application specific traffic engineering.

In contrast, our study presents discoveries of the Internet infrastructure in the region based on measurements performed from access to access networks (whatever their type is – residential, university networks, ISPs, etc.), as we aim at studying how African networks are interconnected to one another from an end-user perspective (i.e. seen from our vantage points). Contrary to [18], we do not only focus on university networks. Instead, we perform our measurements from a wide variety of networks, and at random periods of time covering 2013 to 2016, so as to highlight topological changes. We run full mesh paris-traceroutes among all (324) RIPE Atlas probes in Africa to assess the interdomain routing, and among subsets of probes in countries where sustained traffic localization efforts are made by local networks to offer a glimpse of the impacts of the launch of emerging IXPs. We indeed show varying transit and peering behavior throughout the continent. By studying both existing and recently established IXPs located in Africa, we show that ISPs do peer locally. With five showcases, we evaluate the impact of such infrastructures on end-to-end delays among peers illustrating the benefits of initiatives to promote peering.

The computation scripts used in this study to achieve our goals are all written in the python programming language and query a local MySQL database containing the collected data parsed following a well-defined format. Releasing them as an application accessible by everyone is part of our future work. By contrast, the already released open python code base *IXP Country Jedi* by Aben *et al.* can be used by anyone to create a snapshot of a country and does not require a back-end database [2, 3]. This code produces visualisations that show if paths with end-points within the same country stay in the country and if local IXPs are used. Monthly runs for countries with enough probe diversity are available at [1].

3. Background and Motivation

We present, in this section, an overview of the evolution of the African telecom infrastructure and briefly describe the current state of the African Internet, before concluding with the motivation of our study.

In the early 60's, the incumbent national operators were the sole licensees of the international gateways and phone networks. Since the late 90's, however, there has then been a gradual shift towards the creation of more liberalized telecommunications market environments in Africa. As a result, many competing operators have emerged across the entire range of telecommunications services, such as mobile, fixed, wireless phone, and data services. This has contributed to the partial or full privatization of some of the incumbent operators [14].

By the same token, telecom operators have invested in both domestic long haul and intercontinental optical fiber deployments to reduce their reliance on satellites links [65, 43, 41, 72, 73]. As a consequence, Africa is now linked through 20 submarine cables of various lengths and bandwidth capacities, but the terrestrial optical fiber deployment is still fragmented. Central Africa and the Sahel are the main gaps on the map that segregate other areas of connectivity [72, 67, 69, 42].

Africa's penetration is the lowest of all continents. Only 20.7% of the total 1,186 million inhabitants (by March 2015 [76]) in its 54 countries can access the Internet according to the 2015 ITU statistics [35, 34]. This rate also contrasts with the boom in mobile networks infrastructure and mobile users. In fact, the percentage of Africa's online inhabitants has increased from 2.4% in 2005 to 20.7% in 2015 as shown by [35], while the rate of mobile users has risen from 12.4% to 73.5% in the same period, with a percentage of active mobile-broadband subscriptions of only 17.4% in 2015. These highlight the substantial potential in Internet users that may be reached and positively affected in the region by the network and the web, especially when QoS increases and prices are lowered [44, 22, 35]

A challenge in attaining this goal is to ensure that local networks can easily and cheaply exchange traffic within the region instead of exchanging traffic via remote locations. Studies supported by the African Union in 2008 have shown that Africa spends between $400 and $600 million for intra-African traffic exchange routed overseas [5]. We shed light on this phenomenon and its drawbacks in §5.2 and §5.4. The ability to localize traffic will have significant performance and eventually monetary benefits, since those costs will be saved by local networks. It is clear that without investigating connectivity between African networks, we cannot find where this situation can be improved. These facts prompt us to measure the interdomain topology on the continent over the last four years, since this will serve to capture the evolution of interconnectiv-

ity of African networks and shed light on ISPs' transit habits that could be corrected or encouraged.

4. Methodology

In this section, we first describe the approach followed to identify ISPs playing a key role in transiting Internet traffic between any pair of ASes hosting a RIPE Atlas probe. We then detail the sanity check performed on the collected measurements dataset. We explain how we deal with unresponsive IPs in the traceroutes outputs, *unknown* ASes in the results of the IP to AS mapping process, or loops in the inferred AS paths. Next, we describe our geolocation methodology based on 10 data sources cross-correlated with ping measurements towards the considered IPs. Finally, we explain the methods used to detect peering links, as well as IXPs and their members in the dataset.

4.1. Data Collection

Measuring African networks involves many challenges that influenced our choice for the measurement infrastructure. First, operators are hesitant to deploy foreign devices into their networks, for security and privacy reasons. Second, any device deployed for this purpose has to be robust, as power outages and surges frequently occur in the countries under study. Third, the devices cannot be expensive, since we have no guarantees that all our collaborators will keep them online. Finally, we preferred an open measurement infrastructure, as it provides the means for other network operators and researchers to also utilize the infrastructure and data from this platform to study the African Internet.

To best deal with these challenges, we chose RIPE Atlas as measurements platform. RIPE Atlas consists of over 9,000 online devices deployed worldwide in various locations [63]. Any individual wanting to host a RIPE Atlas probe can do so. For individual users, the probes are free to obtain and to deploy; they are secure, robust against power outages, and require no maintenance. They can perform multiple types of measurements on IPv4 and IPv6, including the ping and the paris-traceroute that we use in this work. The measurement source code is publicly available [16, 15, 50].

In June 2013, Africa only hosted a few (about 83) active RIPE Atlas devices, with almost none in the West. Till then, the RIPE Atlas network coverage of Africa was low and therefore considered by researchers to be a source of limited data [19]. To improve the situation, we deployed 148 RIPE Atlas probes in 69 different networks covering 31 countries, with a special focus on West Africa. RIPE Atlas volunteers and collaborating institutions concurrently deployed a considerable amount of probes in Southern and East Africa, which we also used in this study. These devices are hosted either by ISPs, universities, or by residential networks. None of them are behind a wireless access link, which reduces the impact of last mile latency on our results. Despite all efforts, it is still difficult to get probes in North and Central Africa, where resistance to hosting foreign devices in the network is highest. As a consequence very few ASes/countries from these regions are covered in our study.

From November 2013 to June 2016, we conducted 7 measurement campaigns (Table 1) aimed at investigating the interdomain routing in the region. Instead of running our measurement periodically, on the full timeline, or among the same set of probes, we launched them over random periods to preserve the effect of surprise while collecting the data destined to assess the behavior of the involved networks. There are three other reasons for this choice: first, given the low quality of service experienced by end-users in the region, constantly performing measurements from the hosts' devices may have a negative impact on their Internet access. Second, the RIPE Atlas platform sets, for each user, a maximum number of measurements that we chose not to exceed too often, unlike cases where we run full mesh measurements such as *Meas1A*, *Meas2B* (Table 1). By doing so, we also avoid overloading the probed networks with our measurements' packets. Third, huge loads of measurements consume RIPE Atlas credits at a faster rate than our probes gain them: therefore keeping them running for four years is impossible.

Our measurement campaigns consisted of full mesh paris-traceroutes between the set of probes listed in the column *involved probes* of Table 1. We used paris-traceroute [10] for all our measurements not only to discover path diversity, but also to reduce the number of inconsistencies caused by load balancing when using classic traceroute [77]. The probes performed traceroutes with 16 different paris_id defaults. We used UDP traceroute to reduce the potential bias caused by differentiated traffic handling of ICMP packets [21]. The raw data of our measurements are publicly available in a Technical Report [24].

Careful sanity-checking and cleaning of the collected raw data is an essential step in our analysis. Before filtering, our raw data involved 324 probes hosted in 169 ASes operating in 40 African countries, 626 probes hosted in 380 ASes in 8 EU countries (Belgium, France — FR, Finland, Ireland, Germany — DE, Netherlands — NL, Sweden, and Switzerland), and 329 probes hosted in 195 ASes operating in the US. The geographical spread of all the RIPE Atlas probes used during our measurement campaigns is depicted by Figure 1.

More specifically, Table 2 summarizes the geographical and networking spread of the probes in Africa used in our study. ASes in italics host probes that participate only in IPv6 measurements, and those in bold, probes involved in both IPv4 and IPv6 measurements. Moreover, we put Southern African countries in bold, while West African countries are in italics. We also add the symbol $*$ to the names of countries in which ASes hosting our deployed probes operate.

To give an overview of the granularity of our results,

Name	Type	Involved probes	Period	Frequency	# Traceroutes (Valid Traceroutes) outputs	Coverage of valid Traceroutes outputs	Goal	Used in Sections
Meas1A	*IPv4*	All IPv4 probes in Africa (AF)	2013-11-30 to 2014-04-06	$\approx 3h$	675,421 (593,087) IPv4		Investigate v4 inter-domain routing	§4§5
Meas1B	*IPv4 & IPv6*	All probes in AF countries hosting v6-enabled probes	2013-06-01 to 2014-08-01	$\approx 3h$	408,383 (397,234) IPv4 21,744 (19,593) v6		compare IPv6 to IPv4 interdomain topology	§4§5
Meas1C	*IPv4*	All IPv4 probes in Gambia	2014-08-04 to 2014-08-10	$\approx 1h$	3,161 (2,747) IPv4	238 IPv4 probes hosted in 136 ASes in 35 AF countries & 30 IPv6 probes hosted in 20 ASes in 11 AF countries	Highlight the launch of SIXP in Gambia	§4§5
Meas2A	*IPv4 & IPv6*	All probes in AF	2014-11-07 to 2015-02-18	every week	361,267 (313,268) IPv4 1,584 (970) IPv6		Update our data and track evolution	§4§5
Meas2B	*IPv4*	Only IPv4 probe in Liberia to online IPs in local ASes	2015-08-04 to 2015-08-10	$\approx 200s$	50,960 (45,978) IPv4		Highlight the launch of Liberia IXP	§4§5
Meas2C	*IPv4*	Randomly selected probes in same EU countries (resp. US)	2014-12-08 to 2015-02-23	every week	257,508 (227,021) IPv4	599 (319) IPv4 probes in 373 (190) ASes in 8 EU countries (US)	Compare results within AF countries to those within EU ones and the US	§4§5
Meas2D	*IPv4*	All probes in Madagascar (MG)	2016-04-04 to 2016-08-04	$\approx 200s$	361,344 (318,597) IPv4	11 IPv4 probes in 04 ASes in MG	Highlight the launch of MGIX in MG	§4§5

Table 1: *Datasets collected as parts of this work during our measurements covering 2013 to 2016*

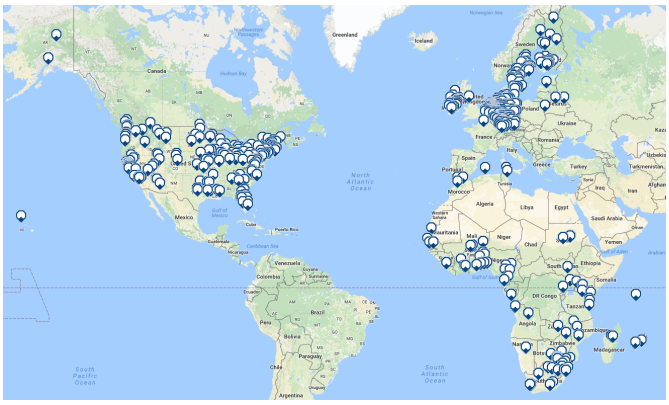


Figure 1: *Geographical spread of the RIPE Atlas probes used in all our 7 measurement campaigns: 324 probes hosted in 169 ASes operating in 40 African countries, 626 probes hosted in 380 ASes in 8 European countries, and 329 probes hosted in 195 ASes operating in the US.*

we compute the percentage of ASes allocated by AFRINIC [7] covered per country as well as the percentage of IPv4 addresses of each country covered by ASes hosting the probes. On average 23.83% of allocated ASes (and 47.6% IPv4 of addresses) are covered per country. While computing these percentages, we include IPv4 spaces of local operators whose ASes have been allocated by other Regional Internet Registries (RIRs).

Using the techniques described below, we first map IP addresses into Country Codes (CCs) to infer the set of countries traversed by the packets on the forward path during each traceroute. Second, we map IP addresses into ASes to infer the AS sequences.

4.2. Data Analysis

4.2.1. IP to Country Code (CC) Mapping

Geolocation of Internet infrastructure is known to be of poor quality [59], especially for IP addresses located in Africa [38]. To geographically locate the 42,412 IPv4 and 1,425 public IPv6 addresses found in the traceroute data as accurately as possible, we analyzed 10 public data sources (DSes) that we cross-correlated with delay measurements, as explained in this section. We used the following DSes :

African Country (#Probes used)	ASes	%ASes	%IP addresses
Angola∗ (3)	36907, 17400, 3741	5.13%	7.08%
Benin∗ (18)	37090, 28683, 37292	33.33%	67.2%
Burkina Faso∗ (7)	25543, 37577, 37073	42.86%	84.72%
Botswana∗ (5)	**14988**, 37678, 37537	14.29%	73.19%
Ivory Coast∗ (6)	29571, 36974	15.38%	73.37%
Congo∗ (1)	37451, 37281	15.39%	9.9%
Cameroon∗ (6)	16637, 15964, 37475, 36905	23.53%	43.3%
Algeria (1)	36947	6.67%	88.14%
Ethiopia∗ (4)	24757	50%	33.3%
Gabon (2)	16058	10%	74.24%
Ghana∗ (7)	30988, 29614, 37012, 37623, 37140, 37047	11.11%	61.625%
Gambia∗ (10)	37309, 37524, 327719, 37323, 25250, 37503	75%	96.23%
Equ. Guinea (1)	22351	N/A	N/A
Kenya∗ (15)	**37061**, 36914, 36866, 37406, 30844, 327748, 12556, 9129, 37662, 15808, 15399	18.27%	20.55%
Liberia∗ (1)	37557	16.67%	9.52%
Lesotho∗ (2)	37057, 3741	10%	43.56%
Libya (1)	21003	12.5%	89.79%
Morocco∗ (3)	**30983**, 36925, 6713, 36884	50%	92.04%
Madagascar∗ (6)	37054, 21042, 37608	20%	62.93%
Mauritania∗ (1)	8657	25%	39.02%
Mauritius∗ (15)	**37708**, **37100**, 37662, 23889,	13.33%	72.31%
Malawi∗ (4)	37098, 37187, 3741	16.67%	12.36%
Mozambique∗ (6)	42235, 31960, 30619, *6939*	13.79%	10.37%
Namibia∗ (5)	36996, 33763, 36877	12.5%	44.21%
Niger∗ (4)	37205, 37385	28.57%	33.12%
Nigeria∗ (3)	30988, 36932, 30988	2.04%	0.62%
Reunion (3)	**37002**, 3215, 49902	66.67%	43.71%
Rwanda∗ (8)	21174, 30844, 37006, 37228, 36934, 16637	30%	69.46%
Seychelles∗ (19)	**36958**, 36867, 37343, 36930	28.57%	1.66%
Sudan∗ (4)	**37197**, 33788	28.57%	6.84%
Senegal∗ (6)	8346, 37196	50%	76.24%
South Sudan∗ (1)	14938, 37406	14.28%	30.77%
Swaziland∗ (1)	**3741**	11.1%	98.67%
Togo∗ (5)	30982, 24691	66.67%	95.24%
Tunisia (11)	*2609*, 37492, 37705	21.43%	83.09%
Tanzania∗ (7)	37045, 36909, **37084**, 37126 12143, 36930, 37182, 33765	13.33%	18.33%
Uganda∗ (6)	327687, 37063, 36997	8.82%	13.78%
South-Africa∗ (109)	37542, 22355, 36874, 36877, 37519, 37457, 37199, 37315, 12258, **33762**, 29975, 37618, 37596, 32653, 327805, **3741**, 16637, 36982, 37253, 37251, 36937, 327750, **37105**, 22351, **6083**, 5713, **2018**, *6939*, 3491, 37519, 37199, 37100, 327813, 37358, **10474**, 37172, 37266, *18931*, 37497, 22690, **37520**, **327817**, 37403, 37312, 11845,		
Zambia∗ (3)	**37043**, 37154, 30844	16.67%	60.15%
Zimbabwe∗ (5)	37204, 30969, 36986, **30844**	11.11%	43.14%

Table 2: *ASes and involved probes per African country: The percentages of ASes and IP addresses are computed based on AFRINIC allocations*

1. OpenIPMap (*OIM*) [62] which aims at obtaining city-level accuracy of Internet infrastructure by crowdsourcing this information from network operators and other interested parties. 25 contributors, mostly operators, currently participate in this effort.
2. Reverse DNS lookups (*RDNS*): we deduced geolocation from location information embedded in host-

names by network operators such as CCs, airport codes, or abbreviated city names. For instance, "xe-3-2-1.**was14**.ipv4.gtt.net." corresponds to a TINET (DE) router located in Washington (US), while "be2321.ccr22.**ams03**.atlas.cogentco.com.", to a Cogent (US) router located in Amsterdam (NL).

3. MaxMind GeoIP2City (*MM*) [49] is a well-known geolocation database often used in applications for end-user geolocation (eg. credit card fraud detection). Therefore, it is most accurate for geolocating end-user IP addresses and far less accurate for router IP addresses that we see in traceroutes.
4. Team Cymru (*TC*) [75], whose data is obtained directly from the RIRs.
5. RIR delegated files: RIRs report their allocations and assignments in so-called *delegated* files that are publicly available [7], [64], [9], [8], [40]. We collected these delegated files up to July 03, 2016.
6. RIR Databases (widely known as *WHOIS*).

Our mechanism to map an IP address to a CC can be described as follows: when all DSes providing an entry for an IP return the same CC, we retain it for that IP. We then use a latency-based method to resolve instances of inconsistency among the DS entries. We launch 3 sets of ping measurements towards each IP from up to 10 random RIPE Atlas probes hosted in each country returned by the DSes.[2] For each group of probes per country, we compute the minimum delay measured and use the CC for which the minimum delay is the lowest. In Table 3, we compare the selected DSes. The coverage column (Cov.) is the percentage of IP addresses in our dataset for which the DS provides a valid country field.[3] The column Trust represents the percentage of IP addresses for which the DS entry is equal to the country that we finally selected for that IP address.

	IPv4 entries		IPv6 entries	
DB	**Cov.**	**Trust**	**Cov.**	**Trust**
OIM	27.01%	98.2%	36.21%	96.06%
RDNS	42.72%	94.75%	49.4%	90.69%
MM	89.74%	85.83%	92.91%	59.17%
TC	90.48%	83.75%	100%	52.34%
AF	16.37%	92.08%	38.46%	75.84%
RI	28.65%	79.35%	22.24%	87.13%
AR	35.84%	87.41%	26.53%	29.78%
AP	0.84%	86.99%	0.07%	0%
LAC	0.002%	100%	0%	0%
WHOIS	94.64%	46.54%	33.75%	24.05%

Table 3: *Comparison of Geolocation databases*

15,412 IPv4 (resp. 472 IPv6) addresses out of the 42,412 IPv4 (resp. 1,425 IPv6) addresses had a consistent CC among all DSes for which a valid entry was available. Our delay-based method to resolve inconsistent answers was then applied to the rest of the IP addresses. We could geolocate all IP addresses that respond to our pings. That is for 18,603 IPv4 (resp. 766 IPv6) addresses, the delay based technique allows us to deduce the country. At the end of this process, 80.2% IPv4 (resp. 86.88% IPv6) addresses of our dataset were associated with a location. We could not find a location for the rest of the IP addresses. They correspond to either offline IP addresses, *i.e.* IP addresses which do not reply to our pings, or cases in which there is no RIPE Atlas probe in one or more possible countries given by the DSes.

With the obtained geolocation data, we can compute the country path corresponding to the IP path of each traceroute output, as defined by [38].

4.2.2. IP to AS Lookup and Raw Data Sanity Check

We first map, using *TC*, public IP addresses of our traceroute data into ASes. We are aware that off-path IP addresses can cause false AS path inferences [48]. However, we believe this so-called "3rd party address" problem to be minor, because network operators are largely unfamiliar with it and do not consider it while using traceroute, as exemplified in [71].

We then apply the following filtering procedure: we keep traceroutes for which the obtained AS Sequence contains source and destination ASes corresponding to the ASes which are known to host the probes. Next, we try and complete remaining path ends based on learned AS adjacencies from this first check: for each non-valid AS sequence, we check if the first AS on the path is a known direct upstream of the source, or the last AS on the path, a known direct downstream of the destination, as observed in the previous set of traceroutes. If these checks succeed, we keep the traceroute as well. However, we only use this second set of inferred AS sequences for AS path analysis, and exclude them from our RTT analysis.

To assess the accuracy of the inferred AS paths, we keep track of intermediate traceroute hops for which the IP address has no entry in *TC*, or for which we did not receive a reply [31]. We respectively refer to them as *unresolved* and *unknown* ASes. We then compress AS paths into AS sequences. *Unresolved* or *unknown* hops found between two resolved hops of the same given AS are considered as belonging to that AS. Consecutive equal AS numbers are compressed into a single AS hop. We only infer an edge between two ASes if there are no *unresolved* or *unknown* hops in the IP path, and if both ASes are consecutive in the AS sequence.

We identify 4,648 traceroutes with inferred AS path loops in the valid outputs of *Meas1A*. The top 3 ASes in those paths with loops are Level3 (US), MainOne (NG), and Data Telecom Service (MG) with respectively 32%, 15%, and 11%. The valid outputs of *Meas1B* contain 1,419 traceroutes with inferred AS paths loops. The top 3 ASes in those paths are InternetSolutions (ZA), MWEB (ZA), and Vox-Telecom (ZA) with respectively 34.9%, 14.7%, and 10.8%. Similar results are found in *Meas2A*. The

[2]The raw data for these delay measurements can be found in [24].

[3]Any entry of these DSes which is not a valid CC is ignored ('EU', 'AP', 'ZZ', 'A1', 'A2', etc)

top 3 ASes in the 1,195 AS paths with loops are InternetSolutions, Swift-Global (MU)[4], and InternetSolutions-KE (KE) with 34.8%, 8.7%, and 8.7% respectively. Since these paths are a small fraction of the total dataset, we filter them out. Note that we find no AS path with loops within the valid AS paths of *Meas1C*, *Meas2C*, and the valid IPv6 paths of *Meas2A*.

By the end of this raw data cleaning method, 87.8% of IPv4 traceroutes are retained for *Meas1A*, while 97.3% of IPv4 traceroutes and 90.1% of IPv6 traceroutes are retained for *Meas1B*. In the meantime, 86.9% of IPv4 traceroutes outputs are selected for *Meas1C*. We keep 90.2% and 88.2% of IPv4 traceroutes outputs for *Meas2B* and *Meas2C* respectively. The corresponding total numbers for all the sub-campaigns are listed in Table 1.

The dataset resulting from this filtering process comprises paris-traceroutes outputs from 243 probes located in 35 African countries (covering over 60% of Africa) hosted in 138 ASes, 599 probes hosted in 373 ASes in 8 European countries, and 319 probes hosted in 190 ASes operating in the US. Moreover, the filtered dataset involves 10,689 IPv4 AS pairs and 224 IPv6 AS pairs in Africa, 33,886 IPv4 AS pairs in Europe (EU), and 31,687 IPv4 AS pairs in the US. Furthermore, we could collect among them in total 27,481 unique IPv4 and 433 IPv6 AS paths within Africa, 38,326 IPv4 within EU, and 36,978 IPv4 AS paths in the US.

Finally, we estimate the RTT between each source and destination AS (denoted *RTT among ASes*) as the difference between the RTT from the source probe to the ingress point of the destination AS, and the RTT from the source probe to the egress point of the source AS. We also estimate the corresponding *RTT among probes IPs* as the RTT recorded at the IP probed by the considered paris-traceroute measurement.

4.2.3. IXP Detection

We explain in this section the process followed to detect IXPs in the dataset. We first build a complete list of IXPs susceptible to exist by collecting IXP information (ASes, prefixes, peers, IP addressing of the IXP) available in African IXP websites, Euro IX, Peeringdb, PCH, IXP toolkit, Telegeography Internet Exchange Map, CAIDA AS relationships dataset [55, 17, 56]. Next, we run the whois command for the subnets in AFRINIC IXP blocks (196.49.0.0/16, 196.216.0.0/16, and 196.223.0.0/16) and extract the corresponding prefixes, organisation-names, and CCs from the outputs. In the rest of this paper, we term the information obtained above *IXPs public datasets*. It involves IXPs of all regions (Africa, EU, North America — NAm, South America, Middle East, Australia, Asia Pacific) registered in those datasets. *IXP-AS* can be defined as the AS allocated by an RIR to an IXP platform.

[4]Swift-Global was a Kenyan ISP that was bought by Liquid Telecom [53]. Its IP addresses are being re-used since then across the region and not just in Mauritius or Kenya

Since mapping an IXP highly depends on the location of the probes used for measurements [11], we check if our probes were present in the networks of some IXP members. It appears that, in the AFRINIC region, 13 of the 37 IXPs (Table 4) under study had no member hosting a probe. We then apply the following techniques to detect IXPs in our traceroutes:

Method1 (M1)—IXP prefix search in IP paths. We consider the IP paths collected for any given pair of ASes in all our measurement campaigns. If any of those paths are via IP prefix in the same subnet as those assigned to an IXP (of Africa, EU, North America, or Asia), we deduce the IP Path is traversing the considered IXP.

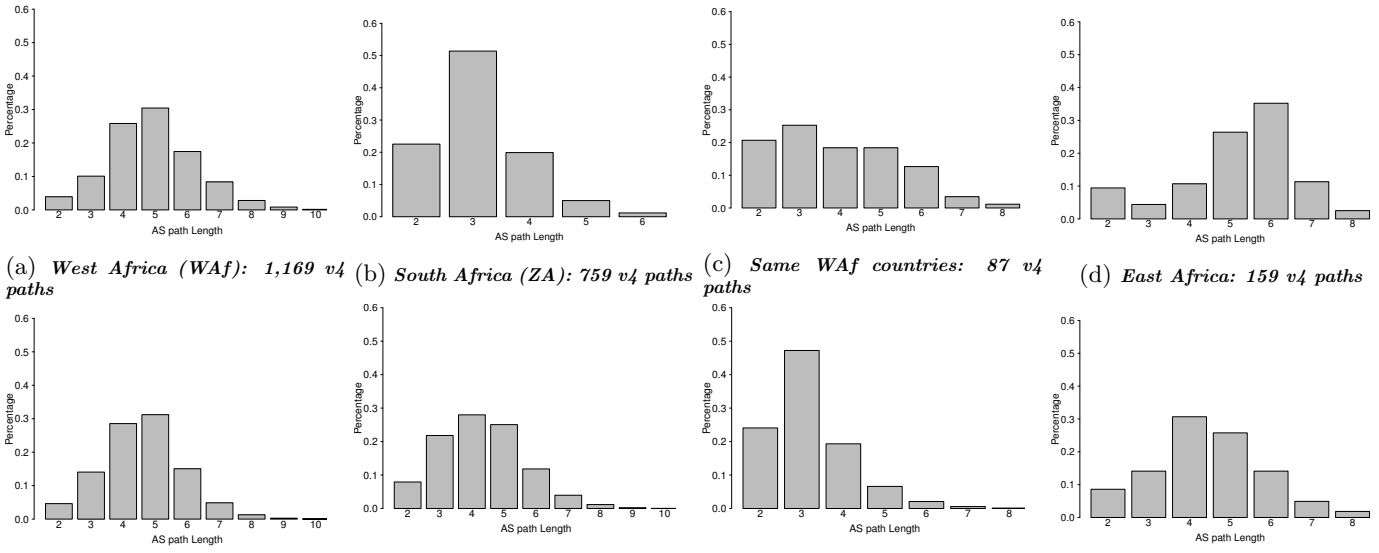
Method2 (M2)—Tracking the launch of an IXP. With this method, we confirm the existence of an IXP whose prefix is not known (e.g. IXPs using RFC1918 address space), by proving its launch based on the collected data (basically showing that during a certain period, the AS path among its peers is greater than 2 and suddenly becomes 2 for the rest of the measurement period, with delays considerably reduced). To this end, we track AS paths length and huge delay drops (among its susceptible peers) by observing the evolution of these metrics over the measurement campaign. In practice, we compute for each AS pair in our dataset the ratio of the average RTT collected for the first 25% of outputs to the one of the last 25%. If this ratio is greater than or equal to 2, we check if simultaneously to the measured RTTs drop, the most common AS path length drops to 2 as well. Note that we do not deduce the detection of an IXP with *M2* unless we find 3 or more peers and the RFC1918 address space traversed in all cases is the same.

4.2.4. Are IXPs prefixes routed on Internet?

To investigate whether IXP prefixes are routed on Internet, we ping all the IP addresses in the ranges of the IXP prefixes from machines whose addresses belong to routed prefixes on Internet. These measurements were launched (*i*) three times from July 16, 2015 to July 25, 2015 from an unique location in Spain and (*ii*) three times from December 28, 2015 to January 03, 2016 from an unique location in the US. Next, we perform DNS lookups of the online IP addresses and deduce if possible the IXP members from ISPs' names embedded into the corresponding hostnames.

4.2.5. Technical description

We parsed the data collected from our measurement campaigns (from a JSON format) into a local MySQL database structured according to a well-defined format. Among others, it stores for each measurement campaign all information related to each traceroute, the IPs geolocation, the results of the IP to CC mapping, the IP to AS mapping, the results of the IXP detection, etc. Our computation scripts are all written in python and run queries



(a) ***West Africa (WAf): 1,169 v4 paths*** (b) ***South Africa (ZA): 759 v4 paths*** (c) ***Same WAf countries: 87 v4 paths*** (d) ***East Africa: 159 v4 paths***

(e) ***Within Africa: 17,487 v4 paths*** (f) ***Southern Africa (SAf): 5,964 v4 paths*** (g) ***Same SAf countries: 864 v4 paths*** (h) ***Within Africa: 163 v6 paths***

Figure 2: *Path length distributions for all (IPv4 & IPv6) AS paths within Africa and for some African sub-regions*

over the MySQL database. Their outputs are stored either into the database or in text files. They are then used as inputs of our Matlab (.fig) plots, pyplots, or R scripts for plotting the graphs included in this paper. Releasing our results as an online application accessible by everyone with updated interfaces showing statistics on the African interdomain is part of our future work.

5. Results

In this section, we first examine the limitations of our dataset. We then highlight the remaining dominance of ISPs based outside Africa to provide interdomain connectivity between studied ASes, except those in ZA. Socioeconomic patterns are also discovered. After that, we illustrate the impact of the intercontinental aspect of paths on the RTTs among African ISPs. Next, we evaluate inter-ISPs communications performance within African countries, European countries and the US. Following that, we map African IXPs in our traceroute dataset and successfully infer 62.2% of the existing IXPs. We detail the inference of Seychelles-IX (SC) and SIXP (GM), and exhibit, as showcases, the launch of Benin-IX (BJ), Liberia-IX (LR), and Madagascar-IX (MG). Finally, we inspect and compare how frequently an AS path among ISPs of our dataset operating on each continent traverses a local IXP.

5.1. Dataset Limitations

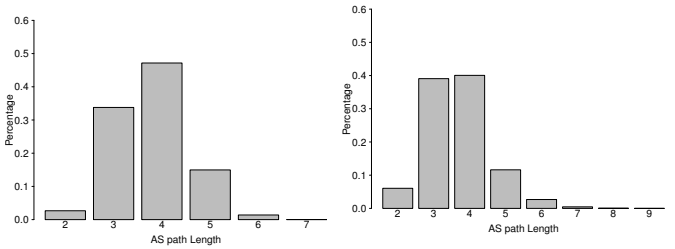
We first acknowledge that the RIPE Atlas infrastructure is constantly evolving, since probe deployment is increasing. This leads us to add new probes to the set of probes that we use on a daily basis. Moreover, not all the probes are online and usable all the time, due to downtime. For diverse reasons detailed in §4, we adopted both full mesh measurements in Africa and measurements among subsets of probes in the same countries in Africa, Europe, and the US (Table 1).

Although the probes used in this study are deployed in 60% of the African countries, our dataset covers in total 13.3% of the ASes, and 43.02% of the IPv4 addresses allocated by AFRINIC. The coverage per delegated IP range is summarized in Table 2. At last, we acknowledge the shortcomings of IP to AS mapping. For instance, 36.4% of the unique v4 AS paths among probes in Africa, 39.7% of those among probes in same EU countries, and 58.5% of those among probes in the US contain at least one either *unknown* or *unresolved* AS, as defined in §4.

5.2. AS path length distribution

We analyze the distribution of the length of AS sequences among pairs of ASes operating in Africa. We notably take a perspective focused on West, Southern, East Africa, and South Africa (ZA). We separate IPv4 from IPv6 paths to highlight differentiated trends. We also carry out a specific analysis for pairs of ASes located within the same country. Moreover, we compute AS path distributions within EU countries and the US for comparison. We only consider the set of paths containing neither *unknown* nor *unresolved* ASes for plotting the graphs of Figures 2 and 3. Thus, the AS paths in those cases could be even longer than what is presented.

On Figure 2(e), we show the AS path length distribution for all the intra-African paths of the dataset. Since ASes in West Africa (*WAf*) are based in geographically collocated countries, one could presume that paths would be shorter. However, based on the specific view provided in Figure 2(a), we discover unusually long AS paths of 5 ASes on average in West African communications. Compared to [23], we find a higher proportion of national paths going through only 3 intermediate ASes (Figure



(a) ***Within the US: 22,285 v4 paths*** (b) ***Within same EU countries: 15,917 v4 paths***

Figure 3: *Path length distributions for IPv4 paths within involved European countries and US*

2(c)). This could be explained by the discovery of new AS paths during *Meas2A*. They connect, for example, Connecteo with Onatel in Burkina Faso (BF), Sonitel with Atlantique Telecom in Niger (NE), AFRICELL-GM with Unique-Solutions in Gambia (GM), and GHANATEL-AS with InternetSolutions in Ghana (GH).

Figures 2(b), 2(d), and 2(f) highlight that short paths tend to be found in Southern Africa (*SAf*), and precisely in ZA for which the set of AS path lengths has a mode of 3. Paths among ASes operating in the same country (Figures 2(b), 2(c), and (g)) are much shorter in ZA than in *WAf*. IPv6 AS paths, of which 77% are observed in *SAf*, tend to be short, reflecting similar peering and localized transit habits as for IPv4 in the region (Figure 2(h)). These observations confirm that focusing solely on measurements from ZA does not provide a representative sample of Internet path characteristics for the rest of Africa.

Figures 3(a) and 3(b) present the AS path length distribution among ASes operating within the US and involved EU countries. AS paths in the US never exceed a length of 7, while those in EU countries attain a maximum length of 9. Similarly to same Southern African countries, and contrary to same West and East African countries (Figure 2), both have a mode of 4. These results highlight a key point: to provide end-users in the African region a better connectivity and an improved QoS for intra-African communications, it is essential to (*i*) shift the average AS path length within West and East Africa regions and thus, within Africa (Figure 2(e)) to 4 (*i.e.* about 70% of the AS paths within Africa should have a length below 5); (*ii*) encourage local ISPs to never exceed an AS path length of 7, in the worse case, for the communications between them.

5.3. Trends in African Interdomain Routing

5.3.1. AS-Centrality

We now study the role of transit played by each ISP found within the AS paths extracted from our dataset. To this end, we define the *"AS-centrality of an AS"*, as the percentage of paths containing that AS, but for which the said AS is neither the source nor the destination. We only account for presence within AS paths among pairs of ASes, radically diverging from betweenness centrality in the AS graph. We then define the concept of *"joint AS-centrality"*, which captures the centrality of tuples of ASes present together on AS paths.

To provide insights for the African sub-regions, we classify the 255 ASes of our dataset into 5 categories, depending on their region of operation: *WAf* (for ASes based in West Africa), *SAf* (Southern Africa), *EAf* (East Africa), *RAf* (ASes operating in Africa but in none of the previous regions), and *Int* – Intercontinental – (all ASes based outside the continent). An AS belongs to the sub-region in which most of the IP addresses allocated by its RIR are geolocated. Any AS having a significant amount of IP addresses located on more than one continent is classified in the *Int* category: we found 87 *Int* ASes.

Figure 4 depicts the AS-centrality of each AS, in the whole set of paths (blue curve), among West African networks (orange curve), and among Southern African networks (black curve). We sort the ASes according to their centrality on the whole set of paths and represent them with different markers given the category to which they belong. In total, 168 ASes had an AS-centrality value greater than 0. We only plot those that play a non-negligible role of transit in Africa, i.e. their AS-centrality is greater than the threshold 0.7%, leaving 98 ASes out.

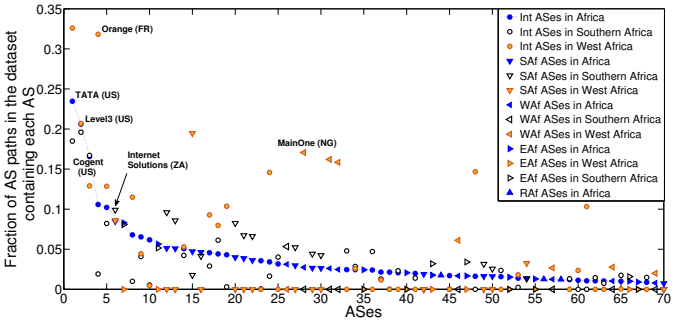


Figure 4: *AS-centrality. ASes are sorted according to their AS centrality within the African interdomain topology (blue curve).*

As indicated by the blue curve, the 4 most central ASes in our view of the IPv4 African interdomain topology are all intercontinental ones: TATA (US) with 23.5% of the 27,481 AS paths, Level3 with 20.6%, Cogent (US), 16.6%, and France Telecom-Orange (FR), 10.6%. 54.9% of the AS pairs are served using at least one of these four ASes. The most central African AS, InternetSolutions, has an AS-centrality of 8.5%. In contrast, France Telecom-Orange becomes the second dominating ISP with an AS-centrality of 31.8% when it comes to paths among ASes in the *WAf* category (orange curve). Meanwhile, TATA and Level3 respectively own 32.6% and 20.7% of the market share. We notice that a relevant percentage of paths (19.5%) connecting *WAf* ASes transit via MTN (ZA). The most central local AS is MainOne, found in 17.1% of the paths.

In contrast, the reliance on *Int* transit providers is lower within the Southern African region; the top 3 ASes remain Level3 with 19.6%, TATA (18.5%), and Cogent (16.7%), but InternetSolutions, SAIX-NET (a private IXP owned by Telkom SA) and MWEB follow with 9.9%, 9.6%,

and 8.2% respectively. *SAf* ASes appear to benefit from diversity in their transit offerings, and resort a lot to peering. Note that the reliance of *SAf* ASes on ISPs based on other African regions is insignificant.

Some ASes, which are not relevant for IPv4 routing, show a high AS-centrality for IPv6 routing. The top 2 ASes in IPv6 are Hurricane Electric (US) with 28.8% and TENET (ZA) with 22.9%. They are followed by TATA (18.7%), Cogent (16.6%), and Liquid Telecom (GB) with 16.6%.

5.3.2. Techno-Economic Insights on Routing Trends

We have also appreciated in our measurements how some techno-economical factors affect transit trends. To give a glimpse of such facts, we present in Figure 5 the AS-centrality of TATA, Level3, and France Telecom-Orange, discussing whether these ASes jointly serve a path or are lying on a path on their own. From the left, the first three triplets of barplots are based on all the paths of the dataset, while the last triplet focuses on the *WAf* category. We use for that graph the color circle: TATA, Level3, and France Telecom-Orange correspond to the primary colors blue, red, and yellow respectively. When all of them appear on a path, that path is classified in the category for which the three colors are mixed (black). If none of them is found, the path is classified in the category colored in grey. All the other colors are obtained by mixing the two primary colors (listed above) of the corresponding ASes.

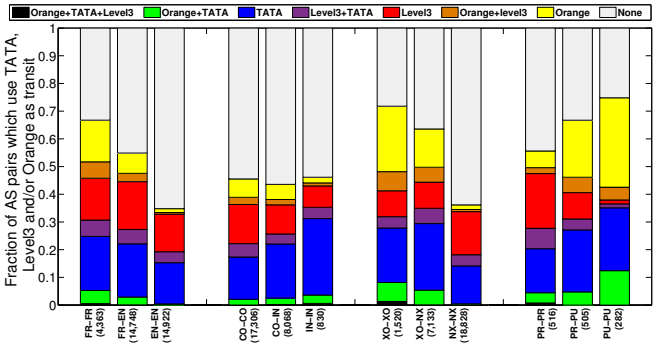


Figure 5: *Joint AS-centrality of AS3356 (Level3, US), AS6453 (TATA, US), and AS5511 (France Telecom-Orange, FR) for paths among various categories of ASes.* ***FR*** *means French-speaking countries,* ***EN*** *English-speaking countries,* ***CO*** *Coastal countries,* ***IN*** *Inland countries,* ***XO*** *Countries in the XAF-XOF region,* ***NX*** *Countries not in the XAF-XOF region,* ***PR*** *Privately owned ASes, and* ***PU*** *stands for Publicly owned ASes.*

ISPs in French-speaking countries mostly rely on France Telecom-Orange, which serves 15% of the West African AS pairs, without TATA or Level3. Another 11.2% of AS pairs are served by France Telecom-Orange, but jointly with TATA or Level3. Nevertheless, France Telecom-Orange completely disappears from our internetworking map when it comes to communications among English-speaking countries. Such diverse transit habits are also observed when classifying ASes according to the monetary region to which they belong. Within the XAF-XOF (CFA Franc) monetary union, France Telecom-Orange has alone a centrality of 23.6%, but is barely present (1.6%) in the market of communications among ISPs operating in countries that do not belong to this union.

From the same figure, we learn that France Telecom-Orange and TATA are lying together on 12.4% of the paths among the publicly owned *WAf* ASes.[5] France Telecom-Orange is lying alone on another 32.3% of these paths. Meanwhile, few publicly owned operators (1.4%) seem to get transit from only Level3. In the same region, however, a relevant proportion of pairs of ASes (19.8%) involving a privately owned AS are served via Level3. Finally, the second triplet of barplots shows that African inland AS pairs rely much more on TATA (35.8%) than on Level3 (13.5%), dominating France Telecom-Orange. Such differences can be explained by the scarcity of Internet transit offerings in inland countries, which mostly rely on Satellite transport companies that peer with Level3 and TATA.

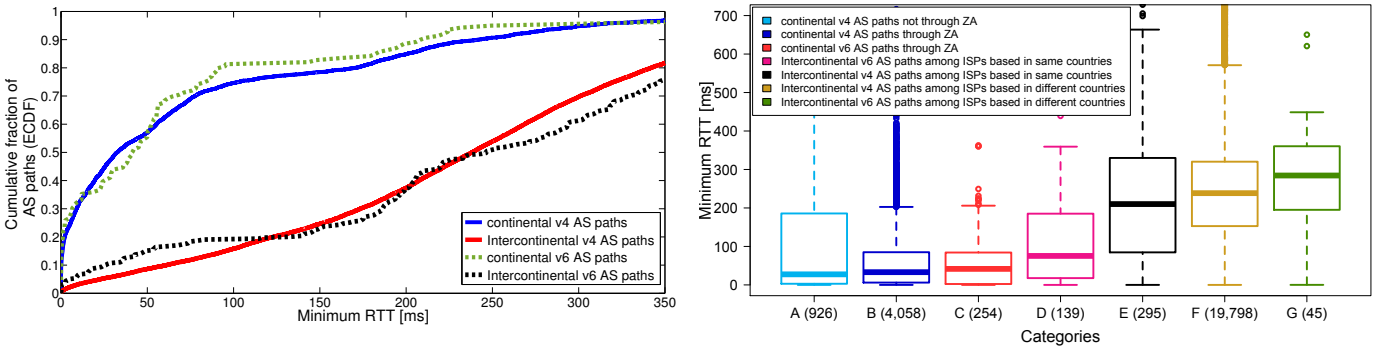
5.4. Impact of transit localization on end-to-end delay

Our objective in this section is to characterize the quality of the different connections based on the observed RTT. To do so, we first identify, per AS path among ISPs operating in Africa, the IP path over which the minimum RTT was observed as well as its corresponding country path. After that, we group AS paths into two categories. Continental AS paths (20.5% of the AS paths in our dataset) are those for which the corresponding country paths only traverse African countries, and which thus stay within Africa. In contrast, intercontinental AS paths (79.5% of the AS paths) traverse at least one node geolocated outside the continent (i.e. the country path contains at least one country outside Africa).

Figure 6(a) shows the CDF of the minimum RTTs among our probes in Africa, comparing continental (IPv4/IPv6) AS paths to intercontinental ones. We notice, for instance, that continental IPv4 AS paths in our dataset have a median of 32.5ms and an interquartile range of 97.9ms, whereas intercontinental AS paths have a median of 238.1ms and an interquartile range of 168.5ms. Also, we observe that approximately 75% of continental v4 AS paths have a delay below 100ms, while this is only 16% for intercontinental AS paths. The results are similar for IPv6 AS paths. They highlight the severe consequences on performance among local ISPs induced by the adoption of intercontinental tromboning of local traffic.

Let us now examine Figure 6(b), a boxplot of the minimum RTTs among our probes, on which boxes are ordered based on their median. Continental paths with very low RTTs mostly correspond to paths among pairs of ASes based in the same country, or those passing through collocated regional ISPs. 82.3% of such paths are through ZA, acting as a regional hub. The IPv4 paths not passing

[5] We categorized the *WAf* ASes as owned by a public or private company, based on gathered private information



(a) *CDF of the minimum RTT among probes in Africa*

(b) *Boxplot of the minimum RTT among probes in Africa*

Figure 6: *Minimum RTT distribution over the AS paths among ISPs operating in African. On the x-axis of figure 8(a) the values between parenthesis correspond to the number of AS paths classified in the corresponding category.*

through ZA have a median of 27.5ms with an interquartile range of 182.7ms, whilst those traversing ZA have a higher median (33.1ms) with a lower interquartile range (78.9ms). Note that all the continental IPv6 paths traverse ZA. Their median is 41.6ms.

Slightly longer RTTs (50 – 150ms) are seen among AS pairs from geographically distant countries. For instance, a path from a KE ISP to a ZA ISP, only served by African transit ISPs, shows a minimum RTT of 80ms. A striking result comes from the presence of very long RTTs in paths that are categorized as continental ones. These IPv4 AS paths are typically those between East African and West African ISPs, which are served by ZA transit ISPs. The following long RTTs ($>$ 2s) are recorded on paths from TZ to ZA via SEACOM (MU), from InternetSolutions to Simbanet (TZ) via KE, or from SAIX-NET to TENET in ZA. They are having a mis-categorization issue, as per our manual checks, since their IP level traceroutes contain many non-answering hops. But we have no data allowing us to certify that they leave the continent.

Intercontinental paths with a low RTT (i.e. $<$ 100ms) also reveal the weakness of geolocation. These AS paths contain *Int* ASes, as per TC, and have also been consistently geolocated in either GB, NL, FR, or the US by the data sources (DSes). These are cases where all DSes are returning the same CC, located outside Africa, although delay-based measurements clearly indicate that the IP address is located on the continent.

Most of the measured RTTs in this category, however, reflect intercontinental transit of continental traffic, with an RTT of around 238.4ms on average. 95.4% of the paths with an RTT between 100ms and 400ms are through EU. Paths with RTTs scattered around 750ms are mostly from and towards ISPs that are served by Satellite providers, routing traffic through another continent. A path in this group is, for example, from Connecteo in Burkina Faso (BF) to AFNET in Ivory Coast (CI), passing through SkyVision, Level3 (in New York), Level3/Global-Crossing (in London), and MTN (ZA). The paths measured with an RTT above 1s are mostly those served via 2 satellite links. For instance, one is from Connecteo in BF to Sonitel in NE, going through the US and EU but arriving in NE via another satellite, provided by IntelSat. Finally, we highlight the RTTs between ISPs operating in same African countries, exchanging packets over intercontinental AS paths. These are notably observed in BJ, MA, Cameroon (CM), Mozambique (MZ), and Mauritius (MU).

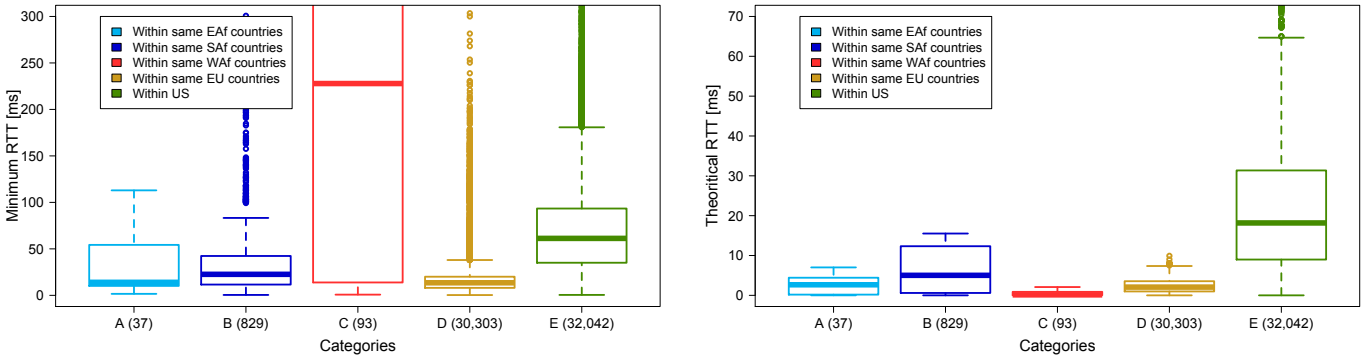
5.5. *Evaluating inter-ISP communications performance within the US, EU, and African countries*

To measure how geographic distances among our probes impact communications performance, we introduce the concept of *normalized RTT* which refers to the ratio of the minimum measured RTT to the best possible RTT. We compute this metric based on traceroutes outputs collected within the US, EU countries, and countries in African sub-regions and compare the results. We only involve African countries gathered by sub-regions in this comparison to avoid a bias towards a given sub-region.

For each AS path (illustrated by Figure 6), we first compute, per corresponding probe pair, the *RTT among probes IPs* (§4.2) as the difference between RTTs recorded at the source and destination probes. We then identify the minimum value $Min_{RTT}(s,d)$ and the corresponding probe pair (s,d). Next, we compute, using great-circle distances [32], the geographic distance $C_h(s,d)$ between the two probes composing the probe pair identified above. After that, we compute the best possible RTT between each such probe pair as the RTT that would have been recorded if the two considered probes s and d were directly communicating via an optical fiber of length $C_h(s,d)$. We refer to this value as the *theoretical RTT per probe pair*, denoted $Th_{RTT}(s,d)$. Bearing in mind that light travels about 1/3 slower through optical fiber cables than it does through a vacuum [60, 61], we estimate $Th_{RTT}(s,d)$ as shown in Equation 1.

$$Th_{RTT}(s,d) = \frac{2 * C_h(s,d)}{2/3\mathbf{c}} = \frac{3 * C_h(s,d)}{c} \qquad (1)$$

With $C_h(s,d)$ the Great-circle distance (km) between probes s and d, and $\mathbf{c}$ the speed of light in vacuum (km/ms).



(a) ***Minimum RTT measured per probe pair***

(b) ***Theoritical RTT per probe pair***

Figure 7: *Distributions of the Minimum RTT measured ($Min_{RTT}(s,d)$) and Theoretical RTT per probe pair ($Th_{RTT}(s,d)$) in same Southern African (SAf), East African (EAf), West African (WAf), European (EU) countries, and in the US*

Figure 7(a) presents the distribution of the minimum RTT values $Min_{RTT}(s,d)$ among pairs of probes (in different ASes) operating within countries on each continent. The median of the empirical RTT values collected within EU countries is 13.5ms, whilst in the US it is 61.3ms. Interestingly, in East, Southern, and West African countries, we record a median (and average) of 14ms (102.9ms), 22.6ms (71ms), and 227.8ms (655.2ms) respectively. As highlighted by Figure 7(b), these median values correspond to respectively 5, 4, and 1,891 times the median of theoretical RTTs $Th_{RTT}(s,d)$. In contrast, the median of the minimum RTTs measured among probes within EU countries and the US correspond to 7 and 3 times that of the theoretical RTTs.

Next, we compute the ratio $R = \frac{Min_{RTT}(s,d)}{Th_{RTT}(s,d)}$ for the set of measurements targeting any pair of probes located in the US, the same European countries, and the same African countries. We obtain a median (and interquartile range) of 6.9 (9.1) for the ratio values corresponding to pairs of ASes operating within EU countries and 3.1 (2.8) in the US, vs. 15.7 (219.8) in East African, 5.1 (27.2) in Southern African countries and, unsurprisingly, 1,940.5 (5,264.4) in West African countries. Combining the above, we suggest that West African operators intensify fiber deployments within countries and implement traffic engineering techniques as well as routing policies aiming at bringing the percentage of AS paths having a ratio below 10 to at least 70% (corresponding to the case of EU countries) and at most 95% (corresponding to the case of the US).

5.6. Mapping African IXPs in our dataset

We next focus our analysis on paths revealing the use of IXPs to exchange traffic. We first built a complete list of IXPs and their information, as explained in §4.2.3. In this data, termed *IXPs public datasets*, we found for the AFRINIC region 29 IXPs to which an AS number has been allocated. The earlier allocations of these ASes were in 2005, while the later ones were in 2015 (Table 4). Table 4 summarises the information related to IXPs of the AFRINIC region. We put the symbol $*$ near the name of IXPs for which no members host our probes. It shows that PeeringDB and PCH are not up to date with regards to the number of peers at each IXP in Africa. Moreover, some IXP members do not register in those datasets or add their prefixes, while some IXPs (e.g. MGIX, DJIBOUTI-DC-IXP, ZINX, LIXP) do not have a website.

5.6.1. Mapped African IXPs

After crossing the collected IXPs information with our traceroute outputs, we detected IPs used to address interfaces to these IXP in our traceroute data. We mapped in our dataset a total of 23 African IXPs located in 16 countries (Table 4) thanks to method *M1*. These IXPs are CINX, JINX, KIXP, NAPAfrica (Johannesburg and Cape Town), SIXP, UIXP, TIX-ASN, MGIX, etc. Among them, 5 IXPs are recently established. With method *M2*, we could prove, for instance, the launch of BENIN-IX and MGIX (§5.6.2). Internet Exchanges BENIN-IX and SIXP were detected by both *M1* and *M2* since they first adopted an RFC1918 address space before acquiring an AFRINIC peering LAN.

We discovered that 11 IXPs have their prefixes routable on the Internet. These correspond to prefixes allocated to either the IXP peering or IXP administration block. It is worth noting that the IP addresses could not be resolved, and nor did the collected Reverse DNS outputs contain the names of the IXP members using the corresponding interfaces. Instead, some DNS lookups contain the name of the IXP (case of SIXP, BENIN-IX). We informed those IXPs through ISOC, and this will be corrected by the peers to avoid security attacks.

Table 5 presents a partial view of the v4 peering matrix of KIXP. It highlights the positive impacts of having each IXP member peering with all the others. We put in green minimum delays between two ISPs when they are present and peer at the IXP. In those cases, the AS path lengths are either 2 or 3. The latter all contain an *unknown* AS (corresponding to IP addresses belonging to KIXP pre-

IXP AS	IXP Name	CC	AS Allocation date	#IPs up (ping from Internet)	IXP mapped?	Mapping Methods	# Peers IXP Websites	#Peers Peering DB	#Peers PCH	#members (local) members found
N/A	DINX	ZA	N/A	0	Yes	M1	N/A	10	5	2 (2)
N/A	WHK-IX/IXP-NAMIBIA	NA	N/A	18	Yes	M1	N/A	4	5	4 (2)
N/A	REUNIX	RE	N/A	0	Yes	M1	N/A	5	10	3 (1)
N/A	KINIX /RDC-IX Kinshasa*	CD	N/A	0	No	N/A	N/A	1	6	N/A
N/A	SEYCHELLES IX	SC	N/A	0	Yes	M1	N/A	N/A	?	4 (4)
N/A	LIBERIA IX	LR	N/A	0	Yes	M1	N/A	N/A	N/A	4 (4)
4558	KIXP	KE	2010-09-22	0	Yes	M1	27	11	29	18 (8)
24736	CAIX*	EG	2007-09-20	0	No	N/A	7	N/A	8	N/A
30997	GIXA-AS*	GH	2005-03-02	89	No	N/A	12	1	24	N/A
33791	TIX-ASN	TZ	2005-08-02	20	Yes	M1	27	11	25	9 (8)
36932	IXPN*	NG	2007-01-16	58	Yes	M1	33	7	30	4 (4)
36946	CIVIX	CI	2007-04-24	10	No	N/A	5	0	5	N/A
37143	ARUSHA-AS/AIXP	TZ	2009-09-02	0	Yes	M1	N/A	N/A	6	8 (8)
37186	NAPAFRICA	ZA	2010-03-15	0	Yes	M1	108	172	41	55 (30)
37195	NAPAFRICA	ZA	2010-04-01	0	Yes	M1	108	172	41	55 (30)
37221	LUSAKA-IXP/ZAMBIAIXP*	ZM	2010-06-14	0	Yes	M1	13	2	13	4 (3)
37224	RINEX c/o RICTA	RW	2010-06-18	0	Yes	M1	9	5	5	14 (4)
37228	RINEX c/o RICTA	RW	2010-06-18	0	Yes	M1	9	9	5	14 (4)
37299	LIXP*	LS	2011-03-08	0	No	N/A	2	0	?	N/A
37355	ZINX	ZW	2011-07-07	0	No	N/A	N/A	N/A	5	N/A
37383	ANG-IXP/ANGOLA-IXP	AO	2011-10-12	0	Yes	M1	12	6	10	2 (1)
37386	UIXP	UG	2011-10-18	23	Yes	M1	17	3	8	5 (4)
37481	CGIX*	CG	2012-07-16	0	No	N/A	6	0	6	N/A
37551	ATI-TUNIXP*	TN	2013-02-05	52	No	N/A	12	2	9	N/A
37635	MOZIX*	MZ	2013-10-04	0	No	N/A	17	3	17	N/A
37651	MIX-AS	MW	2013-11-06	0	Yes	M1	N/A	2	21	2 (2)
37695	BURUNDIX*	BI	2014-03-20	5	No	N/A	2	0	1	N/A
37699	JINX	ZA	2014-05-23	36	Yes	M1	57	53	57	48 (23)
37701	CINX	ZA	2014-05-23	21	Yes	M1	23	21	23	26 (15)
327719	SIXP	GM	2014-01-06	0	Yes	M1, M2	15	0	0	4 (4)
327740	AMSIX- East-Africa	KE	2009-07-24	0	Yes	M1	N/A	N/A	3	2 (2)
327775	AO-IXP*	AO	2014-07-07	6	No	N/A	N/A	N/A	?	N/A
327779	DJIBOUTI-DC-IXP (DjIX)*	DJ	2014-07-31	0	No	N/A	N/A	2	N/A	N/A
327788	ANGONIX*	AO	2014-09-01	0	No	N/A	4	3	3	N/A
327818	BENIN-IX	BJ	2014-11-12	53	Yes	M1, M2	5	2	5	3 (3)
327821	MIXP	MU	2014-11-24	0	No	N/A	N/A	N/A	6	N/A
327834	MGIX	MG	2015-01-29	0	Yes	M1	N/A	N/A	N/A	N/A

Table 4: *List of African IXPs collected in IXPs public datasets as of December 31, 2016. N/A means 'Non Available' and ?, 'Unknown'. The names of the 13 African IXPs for which none of the members was hosting a RIPE Atlas probe during our measurement campaigns are followed by the symbol ∗.*

fix) surrounded by the peers ASes. Minimum RTTs in red correspond to cases in which both ASes (although present) do not exchange traffic via KIXP. Low RTTs with a path length of 2 correspond to cases in which ASes have a private interconnection (e.g KENET-AS and WANANCHI-KE or JTL and WANANCHI-KE), or peer at another Internet Exchange (e.g. KENET-AS and Liquid Telecom at NAPAfrica). High RTTs correspond to cases in which both ASes transit via others to communicate (e.g. JTL and Liquid Telecom).

Liquid Telecom (AS30844) is used by Gupta et *al.* as an example of a network that connects at JINX, and is present but does not peer at KIXP [30]. Nevertheless, our measurement campaigns *Meas1A*, *Meas1B*, and *Meas2A* running from 2013 to 2015, show that Liquid Telecom is present and peers at both IXPs (see Table 5 for details on KIXP peering) as well as at other IXPs (NAPAfrica, Lusaka-IXP, RINEX, and UIXP). At KIXP, however, Liquid Telecom has also been peering using ASNs of the networks they acquired. It is common for large networks to use a BGP Confederations feature during network mergers and acquisitions prior to the implementation of the new organisations network strategy.

Furthermore, we notice that over the same period only 6.8% IPv4 (respectively 6.3% IPv6) AS pairs in Africa have their RTTs dropped to a half of the initial values or more. For 0.4% (resp. 59.8%) IPv4 AS pairs, the AS path length has dropped to 2 (resp. 3), whilst this is only 0.4% (resp. 0.9%) for IPv6 AS pairs. After cross-checking with the IXP prefixes, we could detect that RTTs between SAIX-NET and InternetSolutions changed from 22ms to 6.8ms on average, since they peered at JINX. RTTs from Isocel Telecom to Benin Telecom dropped from 229.3ms to 35.9ms, since they started peering at Benin-IX (§5.6.2), while RTTs from SEACOM-AS to HABARI-CO-TZ-AS dropped from 31.1ms to 0.6ms, after they peered at CINX. We could also detect the drop of RTTs between SIXP platform and GAMTEL in both directions (from 93.7ms to 0.4ms in one and 45.9ms to 22.6ms in another).

	36914	36866	15399	21280	12556	15808	30844
36914		0.6	0.01 (2)	0.1	1.8	0.4	0.3
36866	0.7		1.8 (2)	0.4	0.3	0.001	165 (4)
15399	0.1 (2)	N/A		0.1 (3)	0.4	1.2 (2)	0.8 (3)
21280	0.1	0.9	0.1		0.2	0.7	0.8 (3)
12556	1.7	1.1	0.9	1.3		0.9 (2)	1.8
15808	0.8	N/A	0.1	0.6	0.1 (2)		0.8 (3)
30844	0.1	0.6	0.1 (2)	0.1 (3)	0.1	0.01	
9129	0.4	0.6	0.4	0.8	0.5	N/A	1.5 (3)

Table 5: *Partial KIXP v4 peering matrix extracted from our dataset. When two ASes are present and peering at the IXP (IP belonging to the IXP prefix found in the traceroute output), we put in* ***green*** *the minimum RTTs (in ms) of all the measurements performed between them. RTTs are in* ***red*** *when we have no proof that ASes are peering or when ASes do not peer at KIXP. In those cases, we add the AS path length between parenthesis. N/A corresponds to cases in which we could not have a result due to the absence of probe in one of the AS or to non-valid (and filtered) measurements between the ASes.*

5.6.2. Emergence of recently established IXPs

5.6.2.1. Detection of Seychelles-IX and SIXP (GM). Apart from the information available on the public datasets and IXP websites, we were advised that new IXPs were being deployed in BJ, SC, and GM [52, 66]. We looked for and found those IXPs in our traceroutes. In SC, four members of the IXP were hosting one of our probes at the beginning of the 2nd campaign (*Meas1B*). We could observe a delay around 1ms among each pair of

this clique, formed by CWS-AS, ASIntelvision, Telecom Seychelles Ltd, and Kokonet-BGP.

In the data collected during our third measurement campaign (*Meas1C*), we found probes hosted in networks connected to SIXP: QCell, Netpage, and GAMTEL. The RTTs are around 1.5ms among QCell, NetPage, and SIXP. There is a direct link in both directions between QCell and SIXP. Moreover, GAMTEL and SIXP appear within the path from SIXP to QCell. This hints at the fact that GAMTEL is also a peering partner. Indeed, to peer at SIXP, GAMTEL, and QCell use the IXP address space, while the BGP peering is either direct or via a route-server. The IXP typically holds the AS that announces the IXP address space, which causes its appearance in between the peers at that IXP when using IP to AS mapping with Team Cymru (or data from RIPE RIS). Meanwhile, from GAMTEL to SIXP, our measurements show a direct link. Besides, paths from GAMTEL to QCell all contain SIXP. These prove the success of SIXP, the IXP of GM.

However, not only RTTs between GAMTEL and QCell, but also those between GAMTEL and SIXP fluctuate between low (0.9ms) and high values (460ms) with a median (and mean) of 14.4ms (56ms) and 8.9ms (40.1ms) respectively. After comparison with measurements performed between Netpage and QCell (0.04ms – 18.9ms), we deduce that the link from GAMTEL to the IXP platform is unstable and responsible of such delays.

We then learned from *Meas2A* that RTTs among GAMTEL and QCell had dropped to a set of values with a median of 0.9ms (1.1ms on average); likewise, the corresponding AS sequences have a length of 3, and the IP sequences traverse the IXP. This considerable improvement in the RTT highlights the correction by the peers of the shortcomings emphasised above. In the outputs of *Meas2A*, we also found two others SIXP members: AFRICELL-GM and Unique-Solutions. We then observed that most SIXP members had peered with one another (Table 6): the AS paths often have a length of 3 (with an *unknown AS*), and the IP paths pass via the IXP platform. This fact has a positive impact on the minimum RTTs among any two of them, as those delays are low (0.001ms – 6.6ms).

Nonetheless, AS paths from some members (namely AFRICELL-GM and Unique-Solutions) to the IXP platform often traverse their transit ASes leading to high minimum RTT values (44.9ms – 55.7ms). That is to say, if the peers are sharing resources hosted at the IXP platform, they will still have to pay their transit provider while accessing them, although they are peering locally. Moreover, a properly configured IXP should not have its AS number in the AS path attribute. The fact that it is visible means the IXP is using a Route-Server that does not support transparent AS feature. These shortcomings should be corrected by the peers.

5.6.2.2. On the launch of Benin-IX (BJ). The launch of Benin-IX [13] gave us the opportunity to measure its impact on communications among its different members (Benin Telecom, Isocel Telecom, and OTI Telecom). From December 2013 to the end of our first measurement campaign (*Meas1A*) in April 2014, RTTs measured among those ASes considerably dropped from a median of 326.5ms (314ms on average) between November 30 and December 19, 2013, to a median of 22.1ms (42ms on average) from December 20 to April 6, 2014. According to the traceroute data, those two ASes started peering on December 20, 2014. Figure 8 illustrates the benefit brought by this IXP for end-users and ISPs, depicting RTTs among two members of that IXP, as well as the length of the measured AS sequence. The figure also shows that our probes lost Internet connectivity during the establishment of the IXP, as very few traceroutes succeeded during that period (December 20, 2014 to December 30, 2014).

During *Meas2A*, we observed, however, in both directions that the AS path length was fluctuating between 4 (when the AS sequence traverses Cogent or Tinet SpA and France Telecom-Orange) and 3 (when both ASes peer via the IXP platform) from one period to another. It led to an instability of the delay. We checked and noticed that these changes did not depend on the probes' IP addresses (i.e. IP source or destinations) and hence, were not due to misconfigurations while advertising the peers networks on the BGP session. Consequently, they could be due to the instability of the link between the peers. This situation could be corrected by checking the routers' configurations and introducing redundant connections between peers.

	37309	37524	37323	25350	37503	327719
37309		2.6 (3)	N/A	1.2 (3)	0.3 (3)	0.001 (2)
37524	1.1 (3)		N/A	6.6 (3)	1.5 (3)	55.7 (7)
37323	0.003 (3)	N/A		N/A	N/A	N/A
25250	0.8 (3)	0.03 (3)	N/A		1.1 (3)	0.3 (2)
37503	0.3 (3)	2.4 (3)	N/A	1.5 (2)		44.9 (4)
327719	0.01 (2)	N/A	N/A	0.3 (2)	45.8 (2)	

Table 6: *SIXP v4 peering matrix extracted from our dataset. The number of members is correlated with the number of ASes hosting our probes in Gambia. When two ASes are present and peering at the IXP, we put in* ***green*** *the minimum RTTs in ms (the AS path length) of all the measurements performed between them. Both numbers are in* ***red*** *when this is not the case. N/A stands for Non Available.*

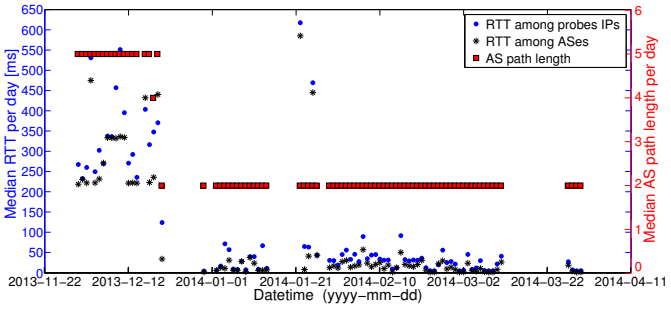


Figure 8: *RTTs among probes in ASes Benin Telecom and Isocel Telecom during Benin-IX (BJ) establishment*

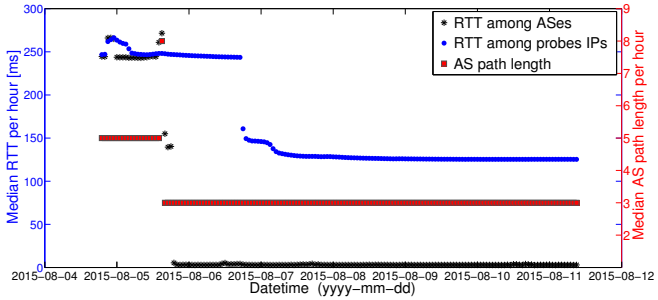
5.6.2.3. On the launch of Liberia-IX. The Liberia IXP was expected to be launched by local networks in August 2015. To measure the impacts, we planned to launch paris-traceroute and ping measurement campaigns among hosts in local ASes. Despite our attempts to previously deploy RIPE Atlas probes in the country, only one probe was online. We therefore scanned all the IP ranges assigned to Liberia (LR) and randomly selected online IP addresses in each local AS. We launched our measurements from the probe towards those IP addresses roughly every 200s (*Meas2C*).

Figure 9 highlights the impact of the launch of Liberia IXP by depicting RTTs among our probe hosted in the NOVAFONE network and carefully selected online IP addresses in LONESTAR, CELLCOM, and LIBTELCO networks. At the beginning of our measurements, NOVAFONE had only one upstream: France Telecom-Orange. The upstream of LIBTELCO was Cogent, while LONESTAR was served by MTN. In contrast, CELLCOM was multihomed and served by Cogent, Belgacom, and DiViNetworks LTD. All networks were transiting for exchanging communications local to the country. Thus, the set of AS paths collected for communications from NOVAFONE to LONESTAR had a median of 5 (via France Telecom-Orange, Cogent, and MTN). The median of the AS paths from NOVAFONE to LIBTELCO was 4 (via France Telecom-Orange and Cogent), while that of AS paths from NOVAFONE to CELLCOM was 5 (via Orange, NTT, and Cogent). The corresponding median of the measured RTTs values among ASes (respectively probes IP addresses), while such routing policies were applied, were 244.1ms (resp. 248.1ms), 238.4ms (resp. 240.4ms), and 131.9ms (resp. 133.9ms). The average RTT among ASes (resp. IP addresses) was 248.1ms (resp. 254.9ms) to LONESTAR, 248.5ms (resp. 250.7ms) to LIBTELCO, and 157.3ms (resp. 165.2ms) to CELLCOM.

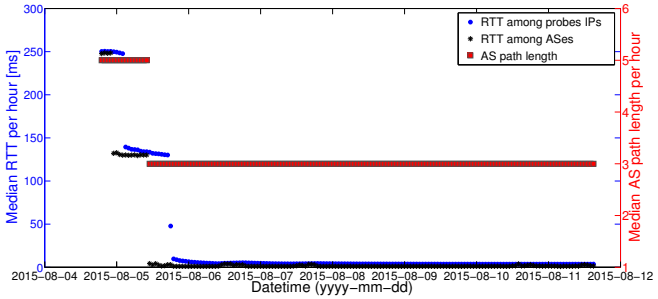
The peering session between NOVAFONE and LIBTELCO was established earlier on August 04, 2015, as shown by Figure 9(c). The AS path therefore dropped to a length of 3 till the end of the measurements since it then contains an *unknown* AS corresponding to an IP address which belongs to the IXP LAN (196.223.44.0/24). Meanwhile, RTTs among ASes (resp. probes IP addresses) dropped to a set of values with a median of 0.9ms (resp. 2.6ms) and a mean of 3.9ms (resp. 6.3ms).

According to the outputs of our measurements, the peering session between NOVAFONE and CELLCOM was then established the day after, August 05, 2015. The AS path had a length of 3 till the end of the measurements due to the same reason as above. The BGP peering led to the drop of RTTs among ASes (respectively probes IP addresses) to values with a median of 1.2ms (resp. 3.6ms) and an average of 2.1ms (4.9ms).

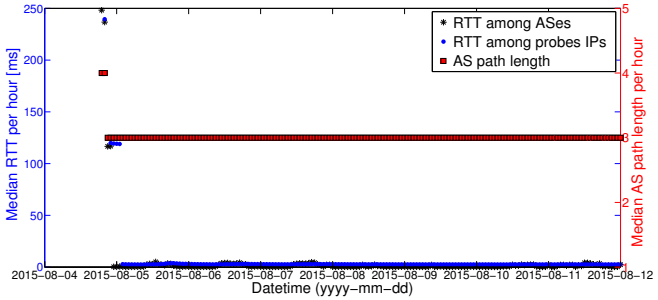
The median length of the AS path per hour between NOVAFONE and LONESTAR first dropped to 3 on August 05, 2015, and RTTs between both ASes to values with a median of 140.9ms. Second, they declined to values



(a) ***from AS37557 (NOVAFONE) to AS37410 (LONESTAR)***



(b) ***from NOVAFONE to AS37094 (CELLCOM)***



(c) ***from NOVAFONE to AS37203 (LIBTELCO)***

Figure 9: *RTTs among ASes / probes IPs in NOVAFONE and other IXP members during Liberia-IX (LR) establishment*

with a median of 2.9ms. However, RTTs among probes IPs stayed at a median of 245.9ms, before decreasing from the day after till the end of the campaign to values with a median of 125.9ms. These high values could be due to either the mediums within the LONESTAR network or its intradomain routing, and the operator should aim at reducing them.

As take-away message, a given NOVAFONE customer communicates with a better QoS with a LIBTELCO, LONESTAR, or CELLCOM customer thanks to LIBERIA-IXP. The IXP also appears as a platform where content or shared ressources can be hosted for the benefit of end-users. In the meantime, all ISPs save their transit costs previously paid for local traffic.

5.6.2.4. MGIX, the Madagascar Internet Exchange. We summarize in this section the key findings from the paris-traceroutes measurements carried out among probes hosted by ASes operating in Madagascar (MG).

To assess peering among local networks, we launched full mesh paris-traceroutes measurements every 200s

among all the probes online in Madagascar from April 04, 2016 to August 04, 2016, as shown by Table 1. Local ASes hosting RIPE Atlas probes during this campaign were AS37037 (Orange Madagascar), AS37054 (TELMA), AS37608 (iRENALA), and AS21042 (GULFSAT-AS). Although AS37303 (AIRTELMADA) host no probe, we also involved online IPs in its allocated prefixes. We made the traceroutes outputs publicly available in [24].

The outputs confirm that ASes that actually peer at MGIX experience the smallest RTTs among their networks. Paths between 2 pairs of ASes are found to traverse MGIX. These are Orange Madagascar –AIRTELMADA and GULFSAT-AS – AIRTELMADA. As shown by Figure 10, the set of AS path lengths corresponding to the first AS pair has a median of 3 (passing via an *unknown* hop) over the measurement period, while the set of RTTs among ASes has a median of 0.9ms with an interquartile range of 0.03ms. For the second AS pair, the set of AS path lengths has a median of 3, while RTTs among ASes have a median of 9.5ms with an interquartile range of 8.6ms. MGIX looking glass [29] lists all 3 ASes among the 7 members of the IXP.

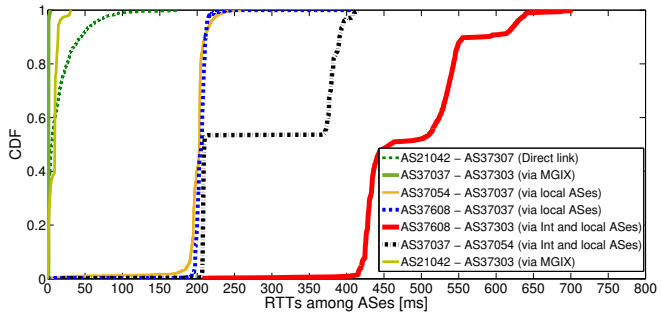


Figure 10: *RTTs among probes in ASes operating in Madagascar, members or not of Madagascar Internet Exchange (MGIX)*

Direct links among local ASes (private peering or not) also lead to a better RTT among those networks. For instance, the link GULFSAT-AS – Orange Madagascar, which was found to never traverse MGIX, has a median of RTT values among ASes of 5.7ms, and an interquartile range of 18.4ms.

Links whose AS paths do not traverse the IXP but traverse instead at least one local AS have a slightly higher RTT. As an example, the AS path lengths of the pair iRENALA – Orange Madagascar have a median of 3 (often traversing TELMA – AS37054) and, from the recorded RTT values, we found a median of 206.1ms with an interquartile range of 8.2ms. Unsurprisingly, iRENALA is not listed as a member of MGIX [29]. Another AS pair classified in this category is TELMA – Orange Madagascar whose corresponding AS paths do not traverse the IXP, although those ASes are members of the IXP. In this case, we registered a median AS path length of 4 and a median RTT value of 202.8ms with an interquartile range of 8.8ms.

Finally, AS pairs whose AS paths do not traverse the IXP and transit at least one intercontinental AS experience the highest RTTs among their networks. For instance, the lengths of AS paths from Orange Madagascar to TELMA have a median of 6 (via France Telecom Orange, Cogent, etc), while RTTs among ASes have a median of 209.5ms with an interquartile range of 172ms. Another example is the AS pair iRENALA – AIRTELMADA for which the median AS path length is 5 (via TELMA, BBIL-AP BHARTI Airtel) and the median RTT among ASes is 458.4ms with an interquartile range of 109.8ms.

5.6.3. A look into other IXPs in the dataset

We now give an insight, per category of measurements, on how frequently an AS path, which originated from and was destined to African countries, European countries, or the US, traverses an IXP located on each continent. To do so, we only consider all discovered AS paths that contain no *unknown* ASes. We classify the measurement outputs per category, listed in Table 7, depending on the region of operation of the AS source and that of the AS destination. We then compute per category the percentage of AS paths that do or do not traverse an IXP, as well as the percentage of paths traversing an IXP located on each continent. Table 7 presents the results.

	via IXP	no IXP	%AS paths via an IXP in Africa	EU	NAm
Among African countries	32.39%	67.6%	16.56%	16.61%	0.08%
Within SAF countries	55.68%	44.31%	52%	3.68%	0%
Within EU countries	67.02%	32.97%	0%	67%	0.01%
Within US	22.57%	77.42%	0%	0.006%	22.56%

Table 7: *Percentage of AS paths passing via an IXP or not in each continent per category of measurements.*

Table 7 shows that no AS path used for communications among the randomly selected probes in same EU countries, or within the US, traverses an IXP located in Africa. It also highlights the extent to which communications between devices located in EU countries traverse an IXP in North America (0.01%) or vice versa (0.006%). These exceptions are indeed paths traversing Equinix (Dallas, San Jose, New York, Ashburn), in the first case, or Equinix Paris and AMS-IX, in the second. Such patterns are quite similar to that exhibited by communications within Southern African countries (52% via an IXP in Africa IXP vs. 3.6% an IXP in EU), although for this sub-region of Africa, all available RIPE Atlas probes are involved.

When all African countries are considered, 16% of AS paths are, however, found to traverse IXPs in Europe. 67.7% of those paths pass via LINX (Juniper/Extreme), 16.7% via AMS-IX, and 12.7% via DE-CIX. Meanwhile, only 16% of the AS paths pass through IXPs in Africa. We identify the top 3 African IXPs as JINX (27.1% of those paths), NAPAfrica Johannesburg (21.7%), and CINX (11.4%). We then evaluate the mean of the set of RTTs between the ingress points of any 2 African ISPs peering at an IXP in Africa to 27.4ms, while it is 70.4ms for any 2 African ISPs peering at an IXP in Europe. Added to our previous results, these differences prove that it is often better in terms of QoS for an ISP operating in Africa

to peer at its closest IXP in Africa than at an IXP located on another continent.

6. Conclusions and Discussion

The purpose of this paper is to understand the global African interdomain routing topology without bias towards any sub-region or country and reveal hidden topological changes that have occurred over the last four years. To achieve this goal, we enhanced the RIPE Atlas infrastructure by around 278% by adding new probes. Overall, we collected traceroutes data at random periods from 2013 to 2016, using all (or subsets of) the 324 probes hosted in 169 ASes operating in 40 African countries, the randomly selected 626 probes hosted in 380 ASes in 8 European countries and the randomly selected 329 probes in 195 ASes operating in the US. We then adopted, as a best effort, a comprehensive method based on 10 data sources combined with ping measurements to geolocate routers' IP addresses with high accuracy. While the IP to AS mapping with Team Cymru services allowed us to obtain the corresponding AS paths, we deduced the corresponding country paths with the geolocated IP addresses.

Our in-depth analysis reveals a diversity of transit operators playing a role in the provision of both v4 and v6 African interdomain paths. It also highlights the dominant reliance on intercontinental ISPs for the establishment of continental connectivity. This leads to long AS paths and RTTs, sometimes among ISPs in the same country. We show a remaining lack of interconnection among African ISPs in IPv4 (South Africa being an exception) confirming the interest of initiatives to promote peering on the continent. We notice striking differences in the transit habits of operators, notably depending on the official language of the country and the monetary region, specifically in West Africa.

From their 2014 experiments, Gupta *et al.* [30] revealed that, by and large, African ISPs are often either *(i)* not present at the local exchanges or *(ii)* do not peer with one another at those exchanges. As we show in this paper, the trends are different when considering a better view of the African Internet from an African point of view involving ASes operating in all its sub-regions. We indeed detected in our traceroutes outputs, 23 of the 37 existing African IXPs and identified local networks as their members. The number of local networks (or not) peering at each discovered African IXP is also precised in our results. Five of the mapped Internet exchanges (Seychelles-IX, Benin-IX, SIXP, Liberia-IX, and MGIX) are recently established. In showcases dedicated to each of them, we highlight the way they reduced RTTs among peers for a better QoS experienced by customers and produced a drop in the AS path length, which led to savings on costs paid for transiting local traffic. All this serves to illustrate how critical it is to have quantity and diversity in the vantage points used in our measurement campaigns so as to better assess interdomain routing on the continent. Thanks to them, we can shed light on the success of projects aimed at fostering IXP establishments in the area. Most of all, we can encourage local operators to continue making sustained efforts in this direction to improve QoS as experienced by local users, while reducing their transit cost.

Mike Jensen proved in [37] that at the end of 1996 only 11 countries had Internet access. He added that, by September 2000, all 54 countries and territories except Liberia had achieved permanent connectivity. Indeed, Liberia was connected in 1999 but lost its link when the local ISP failed to achieve commercial viability. We show in this paper how Liberia has now succeeded in deploying its IXP before other African countries (which are currently targeting the same goal) and has 4 local ISPs connected to it.

The authors of [20] compared different graphs depicting the way communications from South Africa – ZA (in September 2005 and August 2009) and Burkina Faso – BF (in August 2009) to other African countries were provisioned. They reported the absence of direct connections between ZA and the following countries: Democratic Republic of the Congo (CD), Malawi (ML), Namibia (NA), Tanzania (TZ), Rwanda (RW), Uganda (UG), Mozambique (MZ), Kenya (KE), and Zambia (ZM). Meanwhile, Botswana, Swaziland, ML, MZ, NA were found to have direct routes to ZA (i.e. not via Europe). It thus appeared that, the more northerly countries in particular (CD, KE, TZ, RW, UG, and ZM) were not directly connected. Our results reveal that there has been an adoption of direct connections for communications from ZA to those countries, except CD. However, the situation remains the same for BF, which is still connected to most African countries via Europe with satellites links.

As far as public peering is concerned, Johannesburg Internet eXchange (JINX) was, for instance, listed in 2006 among the largest Network Access Points in the world by the author of [47]. The number of IXPs in Africa has then risen, from 8 in 2008 [51] to 18 in 2014 [54, 56]. Actually, in 2013 about a third of African countries hosted an IXP [26], whilst a half (29) host at least one in 2016. The rate of increase is at its highest from July 2014 to July 2015, during which time the number of African IXPs doubled from 18 to 36. The number of African countries hosting those IXPs followed a similar trend (from 13 to 25) [54]. 37 IXPs are currently functional in the region [55].

Despite this positive evolution, operators and stakeholders still have to devote much more effort. First, the number of IXPs in Africa has only increased from 5% of the 435 IXPs in the world in February 2014 to 7.5% of the 491 IXPs globally established by July 2016 [54]. Thus, there are still few African IXPs. In comparison, there are 46 IXPs operating in Latin America and the Caribbean, 93 in North America (US and Canada) and over 130 in Europe [26]. Second, the African interdomain routing is still characterized by the remaining dominance of ISPs based outside Africa for the provision of intra-African communications. Third, Augustin *et al* concluded in [11], while

mapping the IXP substrate, that most IXPs in Africa are small and isolated. Based on information available on their websites and public databases, we found that the average number of African IXP members is 16. As of today, the largest IXPs in Africa are in ZA (with a maximum of about 160 members). Besides, the average number of members at African IXPs is, for instance, lower than the 1/6 of the members of PTT Metro Sao Paulo, where over 300 ASes exchange traffic. It is also insignificant when compared to those of large IXPs in Europe, which are peering over 500 ASes [26]. This confirms that African IXPs are relatively small, compared to those on other continents.

Therefore, local operators need to intensify peering and intra-African traffic localization while increasing fiber deployment within nations and across sub-regions. Each IXP member should also update their information on public datasets (Peeringdb, PCH, IXPs websites, etc.). Moreover, they should make sure their IXP peering LAN is not routable on Internet. Finally, all stakeholders need a public tool which stores or triggers suitable routing policy changes and monitors the African interdomain routing based on real-time measurement data. This web application, currently under construction, will be the focus of a future study. Analyzing peering evolution in the region from 2005 up to now is also part of our future work.

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References

[1] E. Aben. IXP Country Jedi. `http://sg-pub.ripe.net/emile/ixp-country-jedi/latest/`, 2015.

[2] E. Aben. Measuring Countries and IXPs with RIPE Atlas. urlhttps://labs.ripe.net/Members/emileaben/measuring-ixps-with-ripe-atlas, March 23.

[3] E. Aben, D. Mavrommatis, M. Stucchi, A. Strikos, and B. Ellacott. IXP Country Jedi: Probe mesh measurements. `https://github.com/emileaben/ixp-country-jedi`, March 2015.

[4] Africa Program. African Regional and Sub-Regional Organizations: Assessing Their Contributions to Economic Integration and Conflict Management. Technical report, Woodrow Wilson International Center for Scholars, 2008.

[5] African Union (AU). Study On Harmonisation of Telecommunication, Information and Communication Technologies Policies and Regulation in Africa. `http://www.itu.int/ITU-D/projects/ITU_EC_ACP/hipssa/docs/2_Draft_Report_Study_on_Telecom_ICT_Policy_31_March_08.pdf`, March 2008.

[6] African Union (AU). African Internet eXchange System. `http://pages.au.int/axis`, July 2016.

[7] AFRINIC. AFRINIC database. `ftp://ftp.afrinic.net/`, 2016.

[8] APNIC. APNIC database. `ftp://ftp.apnic.net/`, 2016.

[9] ARIN. ARIN database. `ftp://ftp.arin.net/`, 2016.

[10] B. Augustin, X. Cuvellier, B. Orgogozo, F. Viger, T. Friedman, M. Latapy, C. Magnien, and R. Teixera. Avoiding traceroute anomalies with Paris traceroute. In *IMC '06*, pages 153–158, October 2006.

[11] B. Augustin, B. Krishnamurthy, and W. Willinger. IXPs: Mapped? In *IMC '09*, 2009.

[12] V. Bajpai and J. Schönwälder. A Survey on Internet Performance Measurement Platforms and Related Standardization Efforts. volume IEEE Communications Surveys and Tutorials. IEEE, 2015.

[13] Benin-IX. Benin Internet Exchange Point. `https://benin-ix.org.bj/`, 2015.

[14] Beukes-Amiss, M. Three-quarters of African markets have telecoms competition – even then the playing field is not always level. `http://www.oafrica.com/business/three-quarters-of-african-markets-have-telecoms-competition-even-then-the-playing-field-is-not-always-level/`, August 2015.

[15] S. Bortzmeyer. RIPE Atlas probes and the User-Defined Measurements. `https://ripe67.ripe.net/presentations/153-ripe-atlas-udm-api-1.pdf`, October 2013.

[16] R. Bush. RIPE Atlas probes. `https://archive.psg.com/130614.AtlasProbes.pdf`, June 2013.

[17] CAIDA. AS Relationships. `http://www.caida.org/data/as-relationships`, July 2016.

[18] J. Chavula, N. Feamster, A. Bagula, and H. Suleman. Quantifying the Effects of Circuitous Routes on the Latency of Intra-Africa Internet Traffic: A Study of Research and Education Networks. In *AFRICOMM*, 2014.

[19] M. Chetty, S. Sundaresan, S. Muckaden, N. Feamster, and E. Calandro. Measuring Broadband Performance in South Africa. In *ACM DEV-4 '13*, New York, USA, 2013.

[20] L. Cottrell. Routing in Africa. `https://confluence.slac.stanford.edu/display/IEPM/Routing+in+Africa`, 2013.

[21] P. Cristel, C. Luca, V. Stefano, and R. Bush. From Paris to Tokyo: On the suitability of ping to Measure Latency. In *IMC '13*, pages 427–432, 2013.

[22] J. Crowcroft, A. Wolisz, and A. Sathiaseelan. Towards an Affordable Internet Access for Everyone: The Quest for Enabling Universal Service Commitment (Dagstuhl Seminar 14471). *Dagstuhl Reports*, 4(11), 2015.

[23] R. Fanou, P. Francois, and E. Aben. On the Diversity of Interdomain Routing in Africa. In *PAM 2015*. New York, USA, March 2015.

[24] R. Fanou, P. Francois, E. Aben, M. Mwangi, N. Goburdhan, and F. Valera. Four Years Tracking Unreaveled Topology Changes in the African Interdomain: Technical Report. `https://techrep_amc_journal:haHeudcis@fourier.networks.imdea.org/external/techrep_amc_journal/index/index.html`, July 2016.

[25] R. Fanou, G. Tyson, P. Francois, and A. Sathiaseelan. Pushing the Frontier: Exploring the African Web Ecosystem. In *Proceedings of the 25th International Conference on World Wide Web (WWW)*, 2016.

[26] H. Galperin. Connectivity in Latin America and the Caribbean: The role of Internet Exchange Points. Technical Report 20, Internet Society, November 2013.

[27] L. Gao. On Inferring Autonomous System Relationships in the Internet. In *IEEE/ACM Transactions on Networking, vol. 9, no. 6*, December 2001.

[28] J. Gilmore, N. Huysamen, P. Cronje, M. de Klerk, and A. Krzesinski. Mapping the African internet. In *Proceedings Southern African Telecommunication Networks and Applications Conference (SATNAC), Mauritius*, September 2007.

[29] N. Goburdhan. Madagascar IX (MGIX) Looking Glass. `http:`

//wiki.mgix.mg/display/PUB/Peers, April 2016.
[30] A. Gupta, M. Calder, N. Feamster, M. Chetty, E. Calandro, and E. Katz-Bassett. Peering at the Internet's Frontier: A First Look at ISP Interconnectivity in Africa. In *PAM 2014*, 2014.
[31] H. Haddadi, M. Rio, and A. Moore. Network Topologies: Inference, Modeling, and Generation. In *IEEE Communications Surveys and Tutorials*, pages 48–69. IEEE, 2008.
[32] B. Huffaker, M. Fomenkov, D. Plummer, D. Moore, and K. Claffy. Distance metrics in the Internet. In *EEE International, Telecommunications Symposium, (ITS2002)*, 2002.
[33] Y. Hyun. Archipelago Infrastructure. http://www.caida.org/projects/ark.
[34] International Telecommunication Union (ITU). Internet World Stats. https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx, July 2016.
[35] International Telecommunication Union (ITU). Key ICT indicators for developed and developing countries and the world (total and penetration rates). https://www.itu.int/en/ITU-D/Statistics/Documents/statistics/2015/ITU_Key_2005-2015_ICT_data.xls, July 2016.
[36] Internet Society (ISOC). African Union (AU) Selects the Internet Society to Support Establishment of Internet Exchange Points across Africa. http://www.internetsociety.org/news/african-unionau-selects-internet-society-support-establishment-internet-exchange-points-across, August 2012.
[37] M. Jensen. African Internet Report. http://h-net.msu.edu/cgi-bin/logbrowse.pl?trx=vx&list=h-africa&month=0011&week=a&msg=DkgnIo6w/NaHj0hXMIJBrA&user=&pw=, November 2000.
[38] K. Josh, F. Stephanie, and R. Jennifer. Nation-State Routing: Censorship, Wiretapping, and BGP. *CoRR*, abs/0903.3218(http://arxiv.org/abs/0903.3218), 2009.
[39] M. Kende and C. Hurpy. Assessment of the impact of Internet Exchange Points (IXPs) - empirical study of Kenya and Nigeria. Technical Report 59, Internet Society (ISOC), 2012.
[40] LACNIC. LACNIC database. ftp://ftp.lacnic.net/, 2016.
[41] Liquid Telecom. A network like no other. http://liquidtelecom.com/about-us/network-map, July 2016.
[42] G. Mahlknecht. Greg's Cable Map. http://www.cablemap.info/, July 2016.
[43] MainOne Cable System. Mainone cable. https://www.mainonecable.com/network, July 2016.
[44] J. Manyika, A. Cabral, L. Moodley, Yeboah-Amankwah, S. Moraje, M. Chui, J. Anthonyrajah, and A. Leke. Lions go digital: The Internet's transformative potential in Africa. Technical Report 17, McKinsey Global Institute, November 2013.
[45] Z. M. Mao, L. Qiu, J. Wang, and Y. Zhang. On AS-level path inference. In *ACM SIGMETRICS*, pages 339–349, 2005.
[46] Z. M. Mao, J. Rexford, J. Wang, and R. Katz. Towards an Accurate AS-level Traceroute tool. In *Proceedings of ACM SIGCOMM*, pages 365–378, 2003.
[47] Mark and Winther. Tier 1 ISPs: What They Are and Why They Are Important. https://www.us.ntt.net/downloads/papers/IDC_Tier1_ISPs.pdf, May 2006.
[48] L. Matthew and K. Claffy. A Second Look at Detecting Third-Party Addresses in Traceroute Traces with the IP Timestamp Option. http://www.caida.org/~mjl/pubs/tp.pdf.
[49] MaxMind. GeoIP. http://www.maxmind.com/en/geolocation_landing, 2016.
[50] N. Melnikov. Hands-on: RIPE Atlas. https://cnds.eecs.jacob-university.de/users/nmelnikov/aims2013-ripe-atlas.html, AIMS 2013.
[51] M. Michuki. Overview of African IXPs. https://www.isoc.org/isoc/conferences/inet/08/docs/inet2008_mwangi.pdf, June 2008.
[52] M. Michuki. Gambia IXP, an Oasis in the Desert. http://www.internetsociety.org/blog/africa-bureau/2014/08/gambia-ixp-oasis-desert, August 2014.
[53] J. Nyabiage. Stiff competition forces shutdown of Swift Global. http://www.standardmedia.co.ke/business/article/2000086211/stiff-competition-forces-shutdown-of-swift-global, July 2016.
[54] Packet Clearing House (PCH). Internet eXchange Point Directory Reports. https://prefix.pch.net/applications/ixpdir/summary/, April 2016.
[55] Packet Clearing House (PCH). PCH IXP directory. http://prefix.pch.net/images/applications/ixpdir/ip_asn_mapping.txt, 2016.
[56] PeeringDB. http://www.peeringdb.com/private/exchange_list.php.
[57] V. Pejovic, D. Johnson, M. Zheleva, E. Belding, L. Parks, and G. Van Stam. The bandwidth Divide: Obstacles to Efficient Broadband Adoption in Rural Sub-Saharan Africa. In *International Journal of Communication 6*, pages 2467–2491, 2012.
[58] PingER. PingER Project. http://www-iepm.slac.stanford.edu/pinger/, 2013.
[59] I. Poese, S. Uhlig, M. A. Kaafar, B. Donnet, and B. Gueye. IP geolocation databases: Unreliable? 2011.
[60] F. Poletti, N. Wheeler, M. Petrovich, N. Baddela, E. N. Fokoua, J. Hayes, D. Gray, Z. Li, R. Slavík, and D. Richardson. Towards high-capacity fibre-optic communications at the speed of light in vacuum. *Nature Photonics*, 7(4):279–284, 2013.
[61] R. Ramaswami, K. Sivarajan, and G. Sasaki. *Optical networks: a practical perspective*. Morgan Kaufmann, 2009.
[62] RIPE NCC. OpenIPMap database. https://labs.ripe.net/Members/emileaben/infrastructure-geolocation-plan-of-action, December 2013.
[63] RIPE NCC. Global RIPE Atlas Network Coverage. https://atlas.ripe.net/results/maps/network-coverage/, 2016.
[64] RIPE NCC. RIPE NCC database. ftp://ftp.ripe.net/, 2016.
[65] Seacom. Seacom Fiber Network. http://seacom.mu/network/, June 2016.
[66] Serekunda Internet Exchange Point. Serekunda Internet Exchange Point. http://www.sixp.gm/, 2015.
[67] S. Song. Mapping Terrestrial Fibre Optic Cable Projects in Africa. https://afterfibre.net/, March 2014.
[68] S. Song. AfTerFiber Mapping African Terrestrial Fibre Optic Infrastructure. https://www.flickr.com/photos/ssong/albums/72157627195113720, January 2015.
[69] S. Song. African Undersea Cables. https://manypossibilities.net/african-undersea-cables/, 2016.
[70] N. Spring, R. Mahajan, D. Wetherall, and T. Anderson. Measuring ISP Topologies with Rocketfuel. In *IEEE/ACM Transactions on Networking*, pages 931–943, 2004.
[71] R. Steenbergen. Traceroute. http://cluepon.net/ras/traceroute.pdf, 2011.
[72] Submarine Telecoms Forum, Inc. Submarine Telecoms Industry Report 2013. Technical Report 74, Terabit Consulting, 2013.
[73] Submarine Telecoms Forum, Inc. Submarine Telecoms Industry Report 2014. Technical Report 3, Terabit Consulting, 2014.
[74] L. Subramanian, S. Agarwal, J. Rexford, and R. H. Katz. Characterizing the Internet Hierarchy from Multiple Vantage Points. In *Proceedings of IEEE INFOCOM*, page 12, 2002.
[75] Team Cymru. Team Cymru Services. https://www.team-cymru.com/.
[76] United Nations Department of Economic and Social Affairs. World Population prospects. http://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf, June 2016.
[77] J. Van. Traceroute. ftp://ftp.ee.lbl.gov/traceroute.tar.gz, February 1989.
[78] Wikipedia. Regions of the African Union. en.wikipedia.org/wiki/Regions_of_the_African_Union, July 2016.
[79] M. Zennaro, E. Canessa, R. Sreenivasan, A. Rehmatullah, and R. Cottrell. Scientific Measure of Africa's Connectivity. Number 10, pages 55–64. The Massachusetts Institute of Technology Information Technologies and International Development, 2006.



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