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Mobile broadband quality of service analysis using host-based performance measurements

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Mobile broadband since its adoption in Africa has been able to deliver both social and economical dividends to the African people. The increased migration to mobile broadband services in Africa is due to accelerated smartphone adoption rate, increased network roll-out and translation to new and faster technologies. Because technological growth plays a substantial role in society, there is a need for an independent and unbiased assessment of the quality of service offered by mobile broadband infrastructure. However, little work had been carried out on the systematic and consistent investigation of mobile broadband performance monitoring, analysis, evaluation and reporting in Africa. This paper presents a thorough inquiry into the methods employed for end-to-end mobile broadband network measurement, monitoring and experimentation. Policies and recommendations are proposed based on the lessons learnt. Amongst these recommendations is advocacy for the use of a host-based measurement approach for the continued study of mobile broadband performance to assist the various stakeholders to make informed decisions. Furthermore, it was brought to the fore that unsatisfactory broadband speed is not the sole factor that limits the quality of broadband service, and, lastly, significant variations in broadband speed for the same service can be recorded over time due to several complex factors relating to different measurement approaches and conditions.

Keywords: broadband, mobile networks, performance evaluation, quality of service, quality of experience

Introduction

The mobile industry which connects over 3.5 billion people globally to the Internet and more than half a billion people in Africa is the largest Information and Communications Technology (ICT) in history (Bahia and Suardi 2019). Mobile broadband has not only meaningfully extended the reach of the Internet over the past decade but also has actively become the fundamental method of communication for people around the globe (Bold and Davidson 2012). To ensure that everyone, everywhere has access to the Internet with all its opportunities, accelerated work must be done to tackle the inherent challenges that might be encountered. Policies must be put in place to reduce the cost to connect and realize affordable universal access. At the same time, the quality of service (QoS) that online populations encounter when they connect to the Internet must be considered (Woodhouse and Thakur 2018).

Interestingly, mobile broadband since its adoption in Africa has greatly transformed the educational, health care, travel, governance, and news sectors. It has been able to deliver both social and economic dividends to the people of Africa and the world at large (Bold and Davidson 2012). The increased migration to mobile broadband services in Africa is as a result of accelerated smartphone adoption rate, increase network rollout and translation to new and faster technologies (GSM Association 2016).

Since mobile broadband plays an increasingly important role in society, there is, therefore, a strong need for an independent and unbiased assessment of their robustness and performance (quality of service). Mobile cellular networks are enablers of innovation but can also throttle it and cause frustration when network performance falls below expectations (Goel et al. 2016).

From the survey carried out during this paper, little work had been carried out in a systematic and consistent approach to mobile broadband performance monitoring, analysis, and reporting programme in Africa. Nevertheless, to several searches and findings made on the subject matter, three projects (Chetty et al. 2013a; Woodhouse and Thakur 2018; Dahunsi and Akinlabi 2019) stand out in Africa, in regards to assessing broadband and mobile broadband performance in Africa; despite the numerous advantages associated with performance monitoring to all stakeholders and the progress and achievements that have been made in bridging the digital divide in Africa.

(Dahunsi and Akinlabi 2019) presented results of mobile broadband QoS analysis carried out in two Nigeria cities using a host-based and crowdsourcing approach. The second project carried out by (Chetty et al. 2013a) presented the results of the QoSs measurement and analysis of both fixed and mobile broadband connections in South Africa using the router and host-based approaches. The research presented in (Woodhouse and Thakur 2018) employed a software-based approach to benchmark the QoS offered to several low and middle-income countries (LMICs) including some countries in Africa.

The fact remains that the need for continuous monitoring and analysis of mobile broadband performance in Africa cannot be overemphasized. This is because open perceptions of mobile broadband quality apprize end-user behaviour (to making the right choices for his broadband needs). It also enhances regulatory policy as well as marketing, traffic management, and provisioning decisions of the Mobile Network Operators (MNOs). Researchers need network performance data and tools to rapidly test hypotheses and focus on realistic network performance problems. Network operators on their part need to monitor and troubleshoot end-to-end network performance without degrading the base station throughput. Lastly, regulators are expected to tackle the performance challenges and roadblocks for sustained innovation in the mobile space (Goel et al. 2016). It is on this premise of the aforementioned that this paper provides a detailed review of the different approaches to broadband monitoring and evaluation.

This paper provides a comparative overview of existing network measurement platforms for end-to-end mobile network measurement, monitoring, and experimentation which are either classified as hardware or software-based monitoring systems. The measurement efforts expounded in this paper give powerful insights to guide development, research, and regulatory actions. In summary, the following research questions were studied:

(i) what extent has broadband penetration grown in Africa, most especially its dominant fastest-growing consumer markets: Egypt, South Africa, and Nigeria?
(ii) how has QoS been measured and benchmarked in Africa?
(iii) what are the challenges faced in monitoring mobile broadband QoS in developing countries?
(iv) what policy recommendations exist for operators, regulators, and policymakers to enhance mobile broadband QoS offerings in Africa?

The rest of this paper is organized as follows. The next section expounds on mobile broadband and its growth in Africa. The three sections thereafter, respectively discuss the performance evaluation of mobile broadband networks; characterization of mobile broadband networks, and perspectives of stakeholders on end-to-end mobile network monitoring. An overview of different approaches and methodologies that can be employed or adapted for broadband performance monitoring efforts are discussed in the two sections preceding the penultimate section. These aforementioned sections can be studied and adapted for the design of mobile broadband performance monitoring projects. In the final section, a summary of the three broadband performance monitoring projects undertaken in South Africa, some LMICs and Nigeria is given. It is to be noted that the detailed methodology and discussion of results of the performance effort in Nigeria can be found in Dahunsi et al. (2019) and Dahunsi and Akinlabi (2019), respectively. In addition, this section presents some important lessons learnt and challenges likely to be faced when undertaking measurement and analysis of mobile broadband QoS in a developing nation context. Finally, directions for future work and concluding thoughts are then presented.

Mobile broadband and its growth in Africa

Mobile broadband is a term used to describe high-speed Internet service designated to broadcast signals to small and multi-purpose devices such as Tablets and Smartphones (Switcher 2014) in significantly large geographical coverage utilizing wireless technologies (Kim et al. 2006). Mobile broadband networks, the development of mobile devices, and the availability of high capacity Internet services form a crucial part of our daily life. People surf the web, make VoIP calls, send emails, and engage in video conferencing on their respective mobile devices, not minding their locations and what they are doing. Mobile broadband combines the new necessity of high-speed services with mobility (Mitesch, Mishra, and Purohit 2013). Thus, the opportunities are limitless when considering the diverse markets mobile broadband can successfully address.

As of July 2019, it was reported by (Bahia and Suardi 2019) in the UK that the mobile industry connects over 3.5 billion people to the Internet (47% of the global population, contributing at macro level 3.9 trillion Dollars – 4.6% to GDP); by that making it the largest Information Communication Technology in history. GSMA's published report in 2016 revealed that as at the end of 2015, almost half (46%) of the population – equivalent to more than half a billion people in Africa subscribed to mobile broadband services, with the region's three dominant markets – Egypt, Nigeria, and South Africa together accounting for about a third of its total subscriber base (see Figure 1) (GSM Association 2016). Over the next five years, it is expected that an additional 168 million people will be connected by mobile services across Africa, reaching 725 million unique subscribers by 2020. Eight markets will account for the majority of this growth, most notably Nigeria, Ethiopia, and Tanzania, which will together contribute more than a third of new subscribers (GSM Association 2016). Broadband connectivity in Africa has enabled businesses to evolve rapidly and thereby allowing organizations and large enterprises more opportunity to improved performance and operational efficiency.

Broadband adoption in South Africa continues to show significant growth since 2003. According to the recent Independent Communications Authority of South Africa (ICASA) report of 2017 (Naidoo 2017), it was revealed that about 99% of South Africa have been reached with 3G, while 4G connectivity is accessible to approximately 75% of the population. Nevertheless, only 53.4% of South African households have access to the Internet, since not all those who are covered have access to or are using the Internet (Naidoo 2017). Most fixed-line access in South Africa is via Asymmetric Digital Subscriber Line (ADSL) connections. Internet access via a Dongle or 3G USB modem has also become popular because of the mobility of the connection and the relatively low cost of access (Chetty et al. 2013b).

The national broadband policy of South Africa gives expression to the country's vision in the National Development Plan (NDP) of a 'seamless infrastructure by the year 2030 that will bring about a dynamic, connected, and vibrant information society as well as a knowledgeable economy that is more inclusive, equitable and prosperous' (the doc 2013). This seamless information infrastructure is envisioned to be universally available and accessible.

In line with the broader vision of the NDP, the 2020 vision for broadband is that 100% of South Africans will have access to broadband services rated at 2.5% or less of the population's average monthly income by

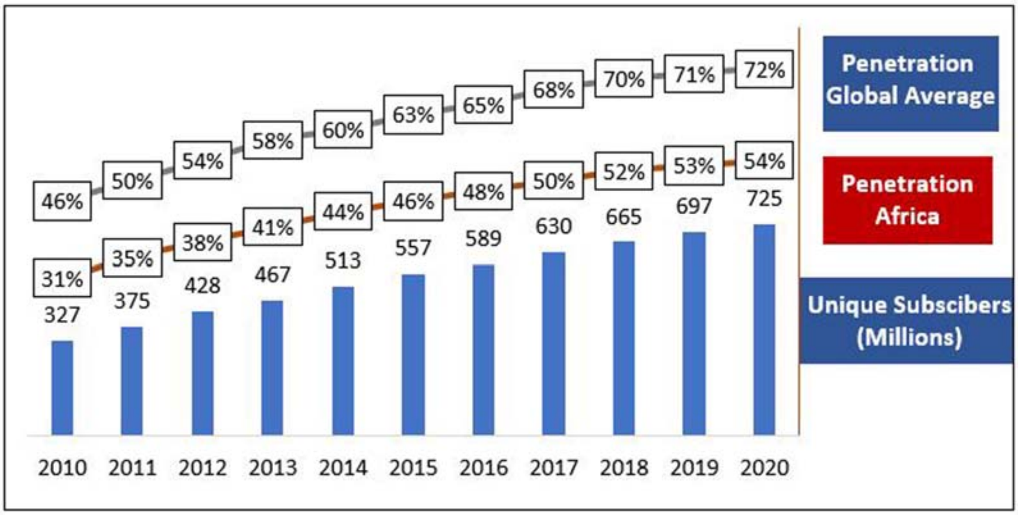

Figure 1: Unique mobile subscribers in Africa (GSM Association 2016).

2020. The overall goal is to achieve a universal average download speed of 100 Mbps by 2030 (the doc 2013). To reach this target progressively, reviewable targets have been set by the Department of Communications, South Africa; starting with an average user experience speed of 5 Mbps. This broadband speed is expected to be available to 50% of the population and subsequently to 90% by 2020. The Independent Communications Authority of South Africa (ICASA) is saddled with the responsibility of monitoring the QoS in line with these set targets (the doc 2013).

Infrastructure improvements have been witnessed only recently in Egypt (since the 2011 revolution) with mobile providers securing 4G licences at the end of 2016. Egypt has one of the largest fixed-line and mobile Internet markets in North Africa (Ookla 2017). As at the end of 2017 in Egypt, the total number of mobile subscribers was 98.76 million with a corresponding mobile penetration of 103% and over half of those with mobiles using it to access the internet in some way. Egyptian citizens have already shown willingness to use technology to aid communication and to build businesses, with half of the population (52%) now using the Internet and half of those using the Internet access it over mobile devices using 2G or 3G technology (blycroft 2017). Egypt's 4G and virtual fixed-line services introduced in 2016 are expected to boost performance, lower consumer cost, create jobs, and also increase competition among the major service providers (Ookla 2017). The growth trend in Egypt favours mobile broadband rather than fixed-line broadband as is the case with South Africa and Nigeria.

Due to the fast development resulting from successful sale of Digital Mobile Licences (DML) in 2001, Nigeria now ranks the largest mobile telecommunication market in Africa. As of December 2019, Nigeria's telecom market has serviced more than 184 million mobile subscibers with 128 million of them having access to Internet services (Federal Ministry of Communications and Digital Economy 2020). Prior to the DML auctions, the Teledensity relating to fixed wireline and wireless networks was below 1%. As at 2019, about 89% of the population can access voice services mainly based on EDGE networks. Mobile networks based on EDGE, 3G and increasingly 4G technologies are currently used for providing Internet in the country (Presidential Committee on Broadband 2013).

The Nigerian Broadband Plan (2013–2018), which came shortly after a decade of the deployment of the mobile telephone in Nigeria was a strategic document designed by the authors to accelerate the development in the Information and Communication Technology sector and bring the developmental impact of broadband Internet access to all Nigerians (Presidential Committee on Broadband 2013). The goal was to accomplish at least 30% broaband penetration, 1.5 Mbps minimum download speeds and at least 80% of the total population connected to 3G. Even though the proposed 30% penetration has been achieved (the broadband penetration rate as at December, 2019 stands at 37.8%), it still has not met the desire of the country as countries in Europe, Asia and America have started deploying 5G technologies but 4G coverage in Nigeria is still very low (Federal Ministry of Communications and Digital Economy 2020).

In the latest broadband plan, which is to span between 2020 and 2025, a minimum of 25 Mbps and 10 Mbps data download speeds are expected to be delivered in the urban and rural areas, respectively, across Nigeria. Also, effective coverage should be available to at least 90% of the population by 2025 at a price, not more than 390 Naira (1.02 Dollars) per 1GB of data. It is hoped that when this plan is carried out, jobs will be created, there will be enhanced socio-economic growth amongst other benefits (Federal Ministry of Communications and Digital Economy 2020).

In short, in Africa, mobile broadband according to (Bold and Davidson 2012) has provided 'unprecedented access to highly personalized Internet and computing experiences.' Mobile broadband dramatically improves productivity, operating efficiencies, and generates revenues for businesses. The Government also benefits from mobile broadband immensely as it improves accident prevention and emergency response via efficient communication, rapid information exchange, enhanced environmental monitoring, and increased productivity. Mobile broadband is capable of providing better reach for consumers, high convenience and enhanced functionalities at low costs. With the adoption of mobile broadband, transformative effects are witnessed in the educational, health care, travel, governance, news sectors, etc.; thereby delivering the economic impacts to governments and individuals all over the world (Bold and Davidson 2012).

Performance evaluation of mobile broadband networks

Performance evaluation is described as an act of quantifying the service delivered by a computer or communication system (Boudec 2011). For instance, Mobile Network Operators need to evaluate mobile broadband services provided to consumers (without degrading the base station throughput); because if consumers are dissatisfied with connectivity and the QoS offered to them, they will in no time port to another network, even though it might cost more than the former.

In past years the problem of measuring and monitoring broadband performance has attracted a lot of attention (Shahid and Ao Shan 2008; SamKnows 2010; Sundaresan et al. 2011; De Donato, Botta, and Pescapé 2014).

The network experience of a larger percentage of Internet users, which is a factor of some QoS and Quality of Experience (QoE) parameters; such as latency, broadband speed (Mehta et al. 2016; Ofcom 2019), connectivity constraints (Kreibich et al. 2010), service availability, type of service, reliability (Rafidah Md Noor 2011), etc. is largely determined by the configuration and management of their access networks (Kreibich et al. 2010).

Quality of service and quality of experience

The QoS achieved by the service provider is a statement of the level of quality achieved and delivered to the customer. This is expressed as values assigned to parameters, which should be the same as specified for the offered QoS so that the two can be compared to determine what was actually achieved to access the level of performance offered (ITU-T 2001). The ITU-T Recommendation E800, adjudged as the most meaningful definition of QoS from the user's perspective, defined QoS as the collective effect of service performance which determines the degree of satisfaction of a user of the service (ITU-T 2001). QoS is clearly a subset of overall quality, where quality is the totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs (ISO 8402).

End users are generally not interested in technical aspects of their connection, but they are interested in what they can do with the connection and the quality of their experience when accessing different applications/services over their Internet connection (ITU-T 2017b). The ITU-T P.10/G.100 defines QoE (Ofcom 2019) as the overall acceptability of an application or service, as perceived subjectively by the end-user. QoE being a multi-dimensional concept encompasses the complete end to end system effects and may be influenced by several systems, user expectations, and context factors. Junaid, in (ITU-T 2017a) listed network, application and device performance, content characteristics, and user past experiences as some of the factors that affect QoE.

There are many cases in which QoS techniques are applied well; nevertheless, network users are not still satisfied. This signals that the acceptable level of service does not always lead to user satisfaction (Junaid 2015). Also, in reality, there is a countless number of complex factors that affect the fate of the traffic traversing a network. It then comes with no surprise that rising complexities in networks of today constantly lead to troubleshooting challenges for novice users and even technical experts. One of the current limitations to the deployment of many services on various networks that are integrated into the Internet is poor or unknown network performance particularly at the edge or access portion of the network (Rafidah Md Noor 2011). Phone hardware, network configuration/setting, radio technology, and underlying network technology, geographical location, time of the day, Service Level Agreement (SLA), Internet Service Provider (ISP) have been identified as factors that affect performance (Wittie et al. 2007; Sundaresan et al. 2010; Chorus 2017).

Characterization of mobile broadband networks

Mobile broadband QoS parameters, also called metrics, characterize the level of service offered to users. Monitoring ensures that users of a particular service get the QoS levels matching what they pay for and it can further be used in the development and implementation of the Service Level Agreement (SLA). QoS parameters can be classified as either objective measurements of the physical attributes of the network or subjective, which requires carrying out customer opinion surveys. The QoS on any communications network or application is usually evaluated through a set of specific metrics (Sundaresan 2014) including throughput (bandwidth), latency (delay), jitter and jitter variations, DNS look-up, packet loss (Sugeng et al. 2015), Bit Error Rate (BER), data transmission success rate, etc.

The last mile is heterogeneous in terms of the technologies and applications used and these have made the QoS assessment methods very challenging. Common network access is either wireline technologies like DSL, cable, or fibre, or wireless technologies like WiMax, UMTS or LTE. Each of these technologies has unique properties, that may affect applications like Web, video streaming, and Voice over IP (VoIP) differently, as each of these distributed applications has different network requirements (Sundaresan 2014). For example, web browsing needs high bandwidth and low latency to DNS and content servers, gaming requires low latency, VoIP needs low jitter so that users can experience a natural conversational interaction and video streaming requires high bandwidth and low jitter to provide a smooth viewing experience, This means that the notion of performance cannot be reduced merely to one number and mobile networks performance parameters cannot be isolated from that of fixed or wireline parameters due to convergence of technologies (as IP packets are employed in both).

The four major metrics which form the basis of QoS and also affect the performance of the Internet and communications networks include packet loss, latency, data transfer speed and jitter. Packet loss, which is the number of packets in a traffic flow that fails to reach its destination (Sugeng et al. 2015) can be measured by sending an echo request consisting of small UDP packets between a QoS client and the measurement server and then wait for a reply. High packet loss results in degradation of performance of interactive applications such as voice and video conferencing, as well as video streaming. On the other hand, latency, which is a critical factor that limits the speed of sending information from a source to the destination can be measured using the ICMP ping command, which sends some ICMP echo packets from a QoS client to the measurement server and then listens for the echo response. In this way, it measures the period between a request for information and the response (Ofcom 2015). Data transfer speed (either upload or download) is a measure of how fast a user can transfer data either to a measurement server or from it. High data transfer speeds are needed for services such as video streaming, heavy files transfer and online gaming (Bauer, Clark, and Lehr 2010). Lastly, jitter has to do with variability of latency over time from point to point. For instance, if the delay in transmission varies too widely on VoIP calls, then the quality of conversation will be greatly degraded. Jitter is generally caused by congestion in an IP network.

End to end mobile network monitoring

All stakeholders – Regulators, Operators, Content-developers, Researchers and Customers alike are beneficiaries of network QoS measurements. However, it is important to consider certain factors before concluding which stakeholder is most qualified to take on the task. Authors of (Citizens 2016) believe that all stakeholders in the telecoms sector of a nation should ensure that improved performance is witnessed in mobile network communications. Nevertheless, stakeholders have differing views on network performance such that the monitoring agents created by each of them capture distinct aspects of network QoS. From a mobile customer perspective, given the nature and mandate of the industry regulators, these regulators are best positioned to measure mobile broadband performance. Each stakeholder's perspective on end to end mobile network monitoring is discussed below.

Developers' view of network performance

Mobile network performance varies across locations, time of the day, devices and operators; hence, it is hard to forecast (Wittie et al. 2007; Sundaresan et al. 2010). Therefore, to maximize the effects of network performance variability on application responsiveness, developers make it a point of duty to always optimize content delivery through lowering of communication frequency (Goel et al. 2016; Chorus 2017), data batching (Bajpai and Schonwalder 2015) and adaptive encoding (ITU-T 2017b). In addition, developers monitor application communication performance and evaluate 'what if scenarios' to be able to understand what manner of optimizations they need to apply and how to configure them (Citizens 2016).

Researchers' view of network performance

Diverse testbeds capable of offering significant flexibility for the execution of a variety of network experiments have been developed by the research community in the past (Australain Competetion and Consumer Commission 2013; Faggiani et al. 2013; Zhuang, Rafetseder, and Cappos 2013; Mao et al. 2014; Miller, Wongsaroj, and Hogg 2014; Yao et al. 2014). Although, collaborations across different groups on how to make these testbeds regularly available and the knowledge of how to use them are limited by practical barriers. Most researchers must develop their measurement and data collection infrastructures (Stanford Linear Accelerator Center 2001) or revive codes that are no longer maintained (Gummadi, Saroiu, and Gribble 2002; MLAB 2107). This is why researchers often decide it is easier and convenient to develop new tools, not minding if past efforts are duplicated and only a small-scale evaluation is achieved (Nandugudi et al. 2013; Balan, Misra, and Lee 2014). Presently, several organizations are working assiduously to limit the barrier to entry and also promote concerted developments of network measurement tools. The research community has also worked to decrease the need for and the cost of redundant experimentation by creating several repositories of wireless network measurement data (Citizens 2016).

Network operators' view of network performance

According to the authors of (Citizens 2016), network operators perform their technical operational monitoring of mobile broadband network performance from base stations and other network elements. They are also interested in end-to-end network measurements from the device's perspective to provide responsive and reliable service at a reasonable operating cost. Another objective of the operators is to simplify and speed up the deployment of new access technologies and over the top services. A key element in all the aforementioned processes is the ability to troubleshoot network performance issues without affecting base station throughput. For the operators to catch a glimpse into end-to-end performance and factors that do affect it, they deploy carrier IQ on mobile devices in their respective networks (Vijayan 2011), but this is met by stiff rejection from the customers (Peckham 2001) who continue to uninstall it on their rooted phones (Apkpure 2013). Against this backdrop, operators are now looking for new approaches which can be used to monitor and troubleshoot customer network performance that can match the scale and efficiency of embedded end-host monitoring provided by carrier IQ. Carrier IQ is an analytics programme for mobile devices that can measure performance and user experience with no visible impact to mobile customers.

Regulators' view of network performance

Regulators owing to their nature and mandate are in the best position to measure mobile network performance. To perform this regulatory duty efficiently, they need monitoring tools that can report the availability, reliability and performance of mobile networks over time. Interestingly, even developers of popular measurement tools struggle to create incentives for longitudinal and widespread measurement (Federal Communications Commission 2014). Few network monitoring tools that have attracted customers rely on them to initiate tests, which in turn limits measurement frequency and by extension measurement data and representativeness (Mao et al. 2014; Miller, Wongsaroj, and Hogg 2014).

Customers' view of network performance

From a consumer's welfare perspective, the flip-side of prices is QoS. It is evident from private use monitoring that not only are prices in Africa high, but speeds also are generally slow and consumers are seldom getting what is advertised and what they pay for (RIA 2014). In highly competitive industrial sectors such as telecommunications, customer satisfaction and loyalty have been identified as critical success factors (Oghojafor et al. 2014). The users of telecommunication services are more demanding in term of QoS and this is the key indicator of customer satisfaction. With the advent of QoE, there are several parameters and activities related to the provision of services that affect customer perception and satisfaction apart from QoS, such as price, support, reliability, repairs procedures etc. Studies in the past such as (Roger 1996) showed that there is a correlation between customer's satisfaction, loyalty and profitability. Furthermore, (Jahanshahi et al. 2011) conclusions reveal that there is a positive correlation between customer service and quality with customer satisfaction and loyalty. When customers are not satisfied with operators' service offerings, they will port to other networks, not minding whether it will cost them more. Also, new customers cannot be attracted. Therefore, customer expectations must be met and even better than they are exceeded.

Developing countries' view of network performance

Despite growing Internet adoption and increasing broadband penetration (though maybe slow) in Africa particularly on mobile devices (Ericsson 2016) and with the arrival of new undersea cables on the east and west coasts (RIA 2014), fairly little is known about the performance of fixed or mobile broadband in several of these countries. The lack of empirical data imposes significant limitations to innovation because broadband performance metrics help users audit their connectivity costs and regulators to make informed decisions about policies and infrastructure investments. Also, broadband performance and cost (Chetty et al. 2012) affect broadband adoption and use (Chen et al. 2010; Wyche et al. 2010) which, in turn, can affect the developmental progress associated with the Internet (Dutta and Bilbao-Osorio 2012). It is for these important reasons that developing countries in the Africa region must take monitoring broadband performance as a necessity.

In the past, one of the main limiting factors to widespread broadband adoption and use in African countries is the high cost of access and the cost of data in general (Chetty et al. 2012) due to the absence of submarine cables and their accompanying abundant bandwidth at the shores of the African continent. Presently the situation has greatly improved. Between 2009 and December 2015, international bandwidth in Africa increased by 20 times thereby reaching 2.034 Terabits per second (Tbps). In North Africa alone, bandwidth increased by 36% in 2015, while in sub-Saharan Africa, it grew by 39%. Submarine cables have been designed with vast capacity and by mid-2015 barely 8% of capacity has been utilized (Economic Commission for Africa 2017).

However, owing to the several advantages associated with the regular monitoring of QoS (relating to making informed decisions about broadband issues) for all stakeholders alike; it is recommended that policy documents that can help address how QoS of broadband connections can be regulated or monitored must be developed by policymakers. Also, the various governments of both the developed and developing markets in Africa should facilitate private investment in local server infrastructure and services to reduce the detrimental effects of factors such as latency on the end-user experience.

To overcome the effects of latency, in particular, governments could facilitate and encourage companies to move content closer to them. Furthermore, the use of superior interconnections and peering that exist between Mobile Network Operators or Internet Service Providers (MNOs/ISPs) through regional and national Internet Exchange Points (IXPs) could be maximized. This will ensure that network traffic takes the shortest or most direct path to its destination where possible.

Methodology: overviews of different methodologies for broadband monitoring and evaluation

This section and the next (i.e. section 7) give an overview of different approaches and methodologies that can be employed or adapted for broadband performance monitoring efforts.

Approaches to broadband monitoring and evaluation

There is no wrong or right method for measuring performance, as each approach has its advantages and drawbacks and various methods are implemented based on resource availability and whether wire-line or mobile (wireless) broadband performance is being measured, not necessarily because it is the best approach available. What is most important is for the measurement approach to produce a rich data set which when aggregated will reflect the true nature of the broadband performance. With the aforesaid in mind, the different approaches which can be used for carrying out performance monitoring and measurements can be classified under the following subheadings:

(a) Hardware and software-based techniques
(b) Active and passive techniques, and

(c) Crowdsourcing techniques

An overview of these approaches is given in Table 1.

Hardware (router) and software (application) based techniques

In hardware-based testing approach, a router or a hardware measuring unit (HMU) equipped with special firmware is employed to measure broadband performance at a specific location (Australain Competetion and Consumer Commission 2013) such as a private residence. A user replaces his router or connects the custom router to his existing router at the location and leaves the router there for the duration of the study. HMUs may be installed at various points on the end-users' connections. However, the most likely position is between the end-users router or modem and their residential network. This allows the HMU to determine when the network is free to run the test – thereby avoiding disrupting the end-user's personal use. Hardware-based testing is only useful for measuring fixed line and fixed wireless connections as opposed to mobile connections. Hardware-based testing has been adopted and implemented in the UK (Ofcom 2019), US (Federal Communication Commission 2016), New Zealand (Epitiro 2013), Canada (SamKnows for European Commission 2013) and South Africa (Chetty et al. 2013b).

The application (software) based testing is carried out from a user's end device or hosts, such as a computer or mobile phone. This test can be conducted in several ways and may involve downloading and installing a test application on the user's device (Desktop, Laptop, Tablet and Smartphone) (Australain Competetion and Consumer Commission 2013) and using this application to run tests either on-demand or periodically using a testing schedule or by clicking on a web application. The software-based approach has been adopted in the UK (Ofcom 2015), India (Mehta et al. 2016) and South Africa (Chetty et al. 2013b).

Active and passive techniques

Monitoring of QoS can also be achieved using passive and active modes. Since both modes have their respective importance, hence, they should be regarded as being complementary. The active monitoring technique mainly relies on the ability to inject test packets into the network being monitored/measured i.e. sending packets to measurement servers and applications, trailing them in a bid to measure the service obtained from the network (Stanford Linear Accelerator Center 2001). Examples include throughput measurement techniques or more comprehensive tools such as Netalyzr (Kreibich et al. 2010) and Portolan (Faggiani et al. 2014). On the other hand, the passive monitoring technique uses devices to watch traffic as it transverses the network. These devices can be special-purpose devices such as a Sniffer or can be built into other devices like routers, switches or hosts (Stanford Linear Accelerator Center 2001). Authors such as Cho et al. (2006), Siekkinen et al. (2007), and Maier et al. (2009) in their research work in Europe, Japan, and France, respectively characterize access networks using the passive traffic measurements approach from DSL provider networks. These studies focused on the traffic patterns and application usage as well as the round-trip latency and broadband speed of residences (Sundaresan et al. 2011).

Standalone and crowdsourcing techniques

Crowdsourcing is a viable strategy for solving very large-scale problems (such as broadband performance monitoring) with the help of the masses, thereby providing a cost-effective network monitoring at a societal scale using a possible, large number of end-users' devices scattered over a wide geographic area (Faggiani et al. 2013). The crowdsourced technique involves a user downloading a test application to his smartphone and either initiating tests himself or an autonomous agent collects data in the background. Numerous opportunities and downsides highlighted in Table 1 accompany crowdsourcing network measurements (Faggiani et al. 2013). The large pool of data available when mobile broadband performance data are crowdsourced give the opportunity (if need be) to choose a subset of users suitable for meeting the specific requirement of the measurement in terms of location, hardware or network operator (carrier). In addition, a diverse view of the participating networks is ensured since a wide diversity of users distributed across the study region will take part in the performance study. Lastly, the variety of real end-user devices involved will allow measurement in realistic scenarios thereby yielding unbiased results.

Review of existing access network monitoring projects

This section introduces some network monitoring projects that are already in existence. It also explains the network tools used during these projects. The section begins with monitoring technologies that use hardware (router) based measurement approach. It then presents application (software) based network monitoring technologies.

Hardware-based network monitoring systems

This section describes some of the popular hardware-based systems that have been employed by Researchers, organizations and policy-makers in the past to measure and report the performance of broadband networks. These systems usually monitor the network traffic and run diagnostics when the Internet is not being used, so that the user is not interrupted when surfing and also ensuring a higher level of accuracy.

Netbeez

NetBeez (Guulay 2015) was born out of the necessity to understand network and application performance in remote locations by providing details of problems end-users encounter when they access the network. NetBeez, which started in 2013 and developed by Gridelli *et al.* has a distributed network monitoring solution that monitors a network from the end user's perspective. The NetBeez methodology involves installing a small hardware agent – Beez (based on the Raspberry Pi platform) in a WAN location. This agent, in turn, simply simulates

Table 1: Comparison of different methodologies for measuring the QoS of internet services.

Method	Advantages	Disadvantages
Hardware	• Requires only a small amount of user's data quota • Offer continuous measurements capable of producing more accurate results. • Little intervention is required after the initial installation	• Fairly expensive as it requires upfront costs to deploy and maintain measurement routers. • Useful for measuring only the performance of wireline connections.
Application (software)	• Many data points can be collected from a large number of users with little additional effort. • Very cost-effective	• Results can adversely be affected by multiple users on the same connection, users' biasness, capabilities and configuration of users' devices • Useful for mobile or wireless broadband connections.
Passive	• Probes only need one connection (less hardware) • Does not dominate the link under test, which makes it a continuous method for end-users.	• Difficult to average tests as the data traffic is not consistent. • Unknown traffic type makes it difficult to test maximum link capacity/capability.
Active	• Allows easy benchmarking of measurements obtained from services provided by different ISPs	• Cost of implementation is quite high. • Requires that the link under test be fully available. • Requires both sending and receiving probes
Crowdsourced	• Harnesses the power of the crowd • Incurs minimal cost. • Capable of providing large-scale user base	• Includes human in the control loop, gives room for bias and errors. • Devices can be operated by the user in an uncontrolled pattern.

end-user activities by continuously testing network services via its wireless interface and then reporting back to a central server via the wired connection (NetBeez 2015); so that if a problem occurs it makes troubleshooting easier by using the diagnostic information from the Raspberry Pi (measurement agent). The NetBeez architecture is comprised of a central server and monitoring agents. The central server can be deployed on-premise as a virtual appliance or in the cloud on providers like Amazon AWS, Microsoft Azure, and Google Cloud (Figure 2). The agents send real-time network availability and performance data to the central server, where the data is processed for alerting and display on the dashboard.

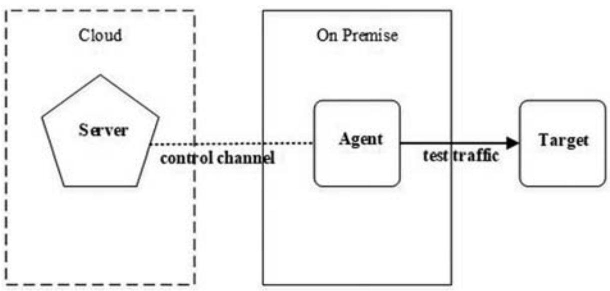

Figure 2: On-premise or Cloud NetBeez architecture (adapted from NetBeez 2015).

The Beez runs six (6) tests which include: DNS resolution latency, ping, round trip time between two hosts, traceroute, the stress of bandwidth and performance of HTTP services. The NetBeez server performs two important functions which are: control of measurement tests and collection of the test results from the various NetBeez agents. NetBeez's management dashboard allows users to generate reports which will assist them in understanding network uptime and the performance for each of the remote locations where the hardware agents are cited (NetBeez n.d.).

BISmark

BISmark, an acronym for Broadband Internet Service Benchmark began in 2010. It is a deployment of home routers running custom software and back-end infrastructure to manage experiments and collects measurements (Sundaresan et al. 2014). BISmark is simply an open-source testbed for deploying measurements and applications in an attempt to better understand the characteristics of broadband access networks. BISmark routers which are major components of the BISmark's system architecture have been deployed in over 20 countries (UK, South Africa, US and Pakistan inclusive) to reliably support both basic routing features and a variety of measurement experiments (Feamster 2014). BISmark, as well as SamKnows (discussed in the next section), has been employed by authors of (Sundaresan et al. 2011) to measure network access link performance. BISmark comprises gateways in the home, a centralized management and data collection server, and several measurement servers. Upload and download throughputs are actively measured using a single-threaded HTTP connection, while other techniques are employed to actively and passively measure link characteristics (Canadi, Barford, and Sommers 2012). Figure 3 shows BISmark's as well as SamKnows' gateway deployment, where the gateway device sits directly behind the modem in the home network. They take measurements both to the last mile router (first non-NAT IP hop on the path) and to wide-area hosts.

Samknows

SamKnows, now a globally renowned network performance company was founded by Sam Crawford, a young software developer, who observed that lots of people who use the Internet complain often about the services they receive from the Internet Service Providers. Sam Crawford hinted that the only way to properly measure a user's Internet performance is from the edge of the home network i.e. at the home router since, at this point, traffic interfering with measurements can be detected (SamKnows 2010). SamKnows specializes in performance evaluation of access networks; it has studied access ISP performance in the United Kingdom (Australain Competetion and Consumer Commission 2013; Ofcom 2015, 2019) and has now contracted with the FCC for a similar study in the United States (Federal Communications Commission 2014, 2016). SamKnows deployed gateways in each participant's home either directly behind the home user's router or behind the home wireless router; the devices can be updated and managed remotely. A Whitebox such as that shown in Figure 4 connected to the user's home router performs the following tests: multi-threaded HTTP download/upload speed test, jitter, latency (both ICMP and UDP), packet loss (both ICMP and UDP), DNS query resolution time, DNS query failure rate, web page load time, availability of connection and web page loading failure rates, based on the client's interest without disturbing his Internet experience. SamKnows throughput measurement method employs parallel TCP streams to be more likely to saturate the upload and download capacity (Canadi, Barford, and Sommers 2012). SamKnows project does not collect any data other than that related to network performance as the privacy of volunteers is of paramount importance to the company. SamKnows testing methodology has been adopted by regulators in countries such as the UK (Ofcom), US (FCC) Brazil, Singapore (IMDA) and all the EU member states (Guulay 2015).

Software-based network monitoring systems

In this section, network monitoring programmes which do not employ dedicated hardware agents for conducting measurements, but rather follow a software-based approach are going to be presented. Deploying software is somewhat easier than a hardware-based approach and can achieve larger scale measurements and coverage. The following are some well-known mobile broadband measuring software.

MIST

In 2007, *Wittie et al*. developed a novel mobile network monitoring tool and architecture called Mobile Internet Services Test (MIST) that evaluates the performance experienced by mobile devices (Wittie et al. 2007). MIST is simply a mobile front-end linked with a server back-end. Throughput, latency and time intervals network performance metrics are measured between the mobile client and the MIST servers and the collected data are saved in a data repository alongside the mobile device configuration and network metadata associated with a test cycle (Wittie et al. 2007). The MIST architecture was designed for mobile developers, to enable them to catch a glimpse of various network characteristics, which can help them build successful applications (Wittie et al. 2007). The main parts of the MIST system as well as its procedure of communication is revealed in Figure 5. MIST application installed on the mobile client saves the user location, MNO and mobile device information one it begins a test cycle. It then proceeds to feed the registration server with the user input data and the accumulated results after a test cycle is over. These information are all stored on the data repository. With the help of the online website, users can review measurements carried out by their mobile clients as well as viewing the graphs relating to their test results. Finally, the function of the connectivity server is to communicate with the mobile client to estimate network performance (Wittie et al. 2007).

Netalyzr

Netalyzr is a network measurement and debugging service for network diagnostics useful for evaluating users' Internet connectivity (Kreibich et al. 2010). Netalyzr's Java applet accessed via a web browser is easy to use for users with a little technical background and forms the foundation of a broad longitudinal survey of edge network behaviour. The app conducts a wide range of measurements which include users Internet access, DNS resolver fidelity and security, IPv6 support, TCP/UDP service reachability, proxying and firewalling, antivirus intervention, content-based download restrictions, latencies, access link buffering, HTTP caching prevalence and correctness, content manipulation, IP address use and translation. Netalyzr's architecture and system implementation since it went live in 2009 has been used by customers more than 1 million times to analyse their connectivity from some 600,000 IP addresses. A major challenge of realizing Netalyzr is the constraint of operating it correctly in the presence of a wide range of failure modes because it is web-driven and pre-disposed to sudden referral surges from specific websites (Goel et al. 2016). Figure 6 shows the screenshot of Netalyzr network measurement and debugging tool.

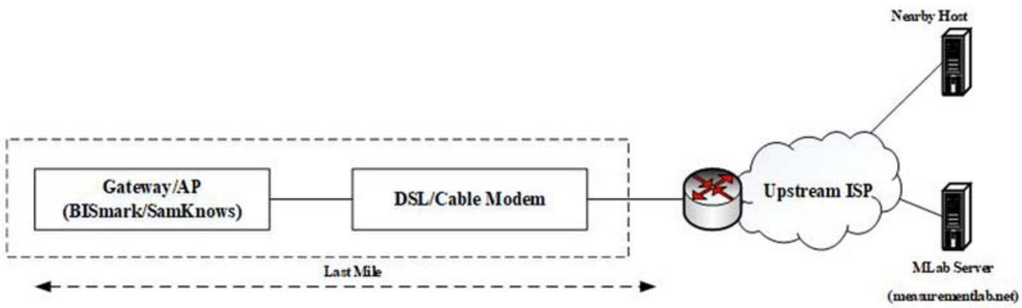

Figure 3: BISmark/SamKnows gateway deployment (Sundaresan et al. 2011).

Speedtest

Speedtest/Ookla is based on a test software and measurement infrastructure developed by Ookla Net Metrics, a developer and vendor of networking testing applications (Bauer, Clark, and Lehr 2010). In addition to Speedtest tool, Ookla also maintains a free testing website known as speedtest.net. The speedtest.net website enables visitors to measure their performance to any public Ookla test server (hosted by partner organizations) around the globe since hundreds of sites around the world currently run it. As of October 2017, Ookla can boost of over 7,168 distributed host servers around the world and over 10 billion tests have been run using the Speedtest/Ookla engine since it became publicly available in 2006 (Ookla n.d.). Ookla test is run between a flash-based applet embedded in a web page and server hosted on a web browser, however, the mobile version runs on Smartphones. Ookla's source code and data which are publicly available have been used by numerous ISPs and researchers in the analysis of Internet access around the world (Guulay 2015). Even though Speedtest enables us to examine broadband performance from a world-wide perspective, Speedtest mobile application lacks a programming interface to allow users to automate and schedule experiments (Goel et al. 2016). Figure 7 shows the screenshots of the home and results pages of Ookla/Speedtest application.

Mobiperf

A team of researchers in the RobustNet Research Group at the University of Michigan in 2009, developed MobiPerf, a mobile application and handy network tool to collect anonymous network measurement information directly from end-users (Huang et al. 2011). It is a useful tool that runs on Android and iPhone enabled mobile devices. MobiPerf allows experiments to be parallelized to reduce its overall running time. It also allows a user to have good knowledge of his Smartphone's network properties, such as local/global/gateway IP addresses, cell ID, GPS (latitude and longitude), upload/download bandwidth, signal strength, DNS lookup latency, PING latencies, TCP connection establishment latencies, HTTP benchmark downloading latencies and many more. Figure 8 shows the screenshots of MobiPerf's home, test-run and results pages. MobiPerf has a vast number of measurements, therefore the choice of a single server employed by MobiPerf's developers is limiting. MobiPerf provides its users with a limited network measurement capability between mobile devices and servers, as opposed to testbeds (e.g. BISmark). MobiPerf allows users to choose from only predefined measurements, which limits the tool's flexibility (Goel et al. 2016).

MBPerf

In 2018, Researchers at The Federal University of Technology, Akure (FUTA) undertook a study to evaluate the performance of EDGE (2G family), UMTS and

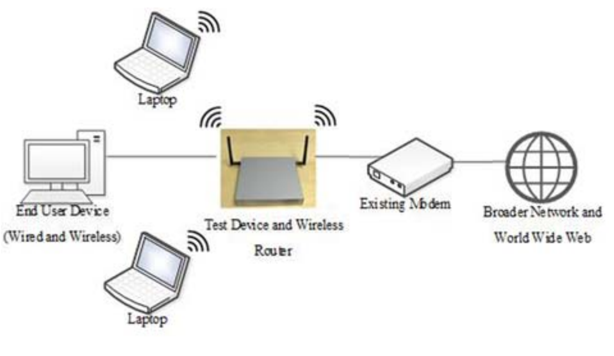

Figure 4: SamKnows router based network monitoring approach architecture (adapted from Australain Competetion and Consumer Commission 2013).

Figure 5: MIST architecture and communication protocol (adapted from Wittie et al. 2007).

Figure 6: Netalyzr network debugging tool (Citizens 2016).

HSPA (3G family) networks as delivered to 100 Android Smartphones in different areas of Akure and Ibadan (in Nigeria) where the 4 target MNOs have an adequate presence and provide network services (Dahunsi and Akinlabi 2019). Data were collected between January and March 2018 on mobile connections using a crowdsourced and host-based approach. Mobile Broadband Performance (MBPerf), which was the QoS application developed was installed on volunteers' Android Smartphones to measure 4 selected mobile broadband QoS metrics – download and upload speeds, latency and DNS lookup; including some basic network properties such as network carrier name, network type, cell ID, Location Area Code (LAC), Received Signal Strength (RSS) and the build information of the user's Smartphone (Akinlabi 2019). MBPerf's source code was written in Java programming language while its User Interfaces were designed using XML.

Major bottlenecks were introduced because tests were conducted toward an international server. Nevertheless, the speeds (download and upload) and latency measurement conducted toward the international server help reflect bottlenecks that users experience along a wide area path (Akinlabi 2019). In addition, most contents users assess are hosted on international servers, therefore conducting tests toward an international facility will allow measurements in more realistic scenarios (Feamster 2014). MBPerf ran tests and collected the required metadata from volunteers' Smartphones as a background service, taking measurements hourly throughout the day. This high-frequency testing schedule was allowed to achieve robust data set even though users' data consumption increase with frequency of use (Akinlabi 2019). Volunteers were provided with the numerical summaries of their mobile connections' performances on their mobile phones. Only the Android platform was used to carry-out performance measurements to ensure a uniform Operating System (OS) for all volunteers; furthermore, the OS is also widespread, popular and flexible. Figure 9 shows the screenshot of the home and results pages of MBPerf QoS application.

Results and discussion

This section reports on the results that emanated from the analysis of the performance data collected from a pilot study of measurement of broadband performance in South Africa carried out by Research ICT Africa (RIA) in collaboration with (Chetty et al. 2013a) and that carried out by (Dahunsi and Akinlabi 2019) at The Federal University of Technology, Akure. The results from (Chetty et al. 2013a) were purposely presented because they emanate from a study that embodies an archetypal method for monitoring broadband performance in developing countries. Also, the results of the collaboration of authors of Bold and Davidson 2012 and New America's Open Technology Institute to leverage on M-Lab's dataset to benchmark the actual QoS in some LMICs are also presented. The challenges faced and lessons learnt from these studies are presented afterwards.

Africa and broadband performance monitoring: a case study of South Africa, Egypt and Nigeria

The question of whether Africans who have access to the Internet are experiencing broadband services that are delivering on the claims (promises) made by their MNOs is still very difficult to answer; because up till now, little has been done in the aspect of monitoring and reporting the performance of broadband in Africa, despite the numerous advantages associated with this activity to all stakeholders. Accessing QoS in a given country requires robust and objective data which oftentimes are expensive to obtain and out of date; because it is not regularly collected or otherwise not available to the public (Woodhouse and Thakur 2018). National regulatory authorities by and large do not monitor performance and if they do so, they do not report on their findings. Measuring broadband performance is further complicated because mobile devices are increasingly becoming the key entry point for Internet adoption on the continent and therefore monitoring mobile broadband is as relevant as monitoring fixed broadband performance. Mobile broadband is now the primary means of access to the Internet in Africa for individuals unlike in mature markets due to its lower cost compared to similar fixed-line offerings (Skouby and Williams 2014).

Measuring and reporting the performance of both broadband and mobile broadband networks has been a hot topic of research and a continuous activity performed by stakeholders in the telecoms industry in the developed world (Federal Communications Commission 2014, 2016; Ofcom 2015, 2019). It is even more compelling to investigate and understand the QoS of mobile broadband connections that is the most prevalent in Africa because it serves as a substitute for the high cost of

Figure 7: Home and results pages of Ookla/Speedtest network performance application (Goel et al. 2016).

fixed-line and fixed broadband. To the best of our knowledge concerning findings from the literature, three projects stand out in Africa presently with regards to assessing broadband and mobile broadband performance in Africa. The projects are highlighted below

Research ICT Africa (RIA) sought to assess fixed-line and wireless broadband services in six African countries: Ghana, Kenya, Nigeria, Tunisia, Uganda and South Africa. As of 2014, RIA has established a close working relationship with partners in each of these target countries (RIA 2014). In all the 6 target countries, RIA had only been able to collaborate fully with Chetty et al. (2013a, 2013b) to carry out a pilot study of both fixed and mobile broadband connections in South Africa using software implemented on mobile phones (Speedtest app) and home routers (BISmark) to address challenges that are unique to the developing world. This study was acclaimed by Chetty et al. (2013a, 2013b) as an archetypal method for monitoring broadband performance in developing countries. Studies conducted by (Chetty et al. 2013a, 2013b) between February and May 2013 in South Africa investigated the performance of the users' fixed and mobile broadband connections to know if they get the performance advertised by the Internet Service Providers (ISPs). Summarily, the result from this QoS monitoring effort based on measuring broadband performance through mobile and router applications suggested the following: first, users are not getting the speeds that their ISPs advertise; second, mobile broadband users commonly achieve higher throughput than fixed line users, although the performance that they achieve is variable; and lastly, speed (i.e. throughput) is not the only limiting

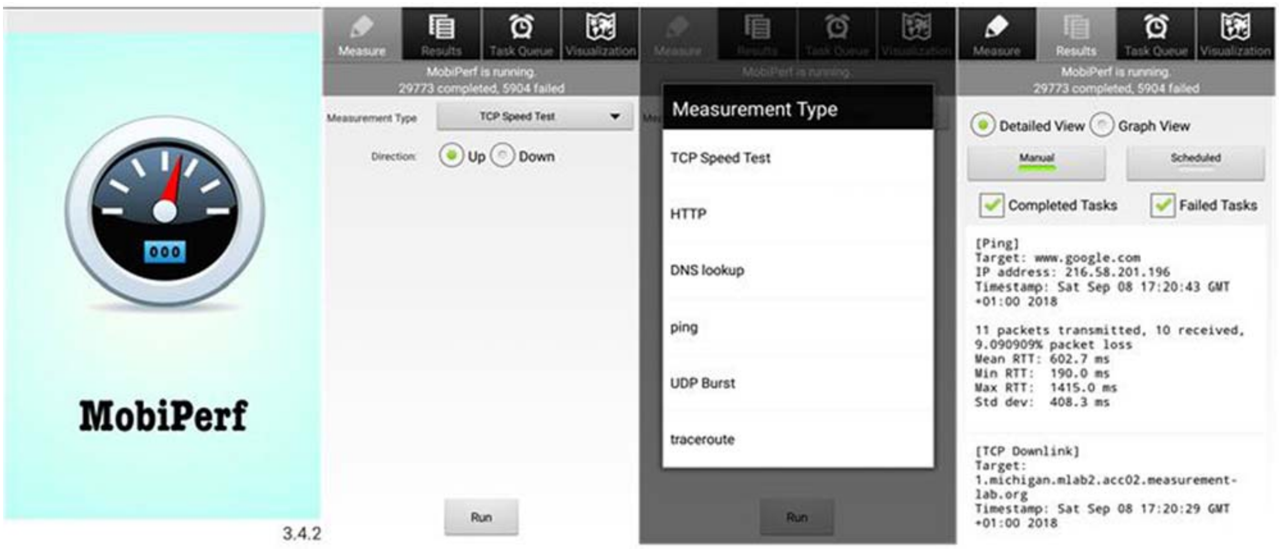

Figure 8: Home, test-run and results pages of MobiPerf network performance application.

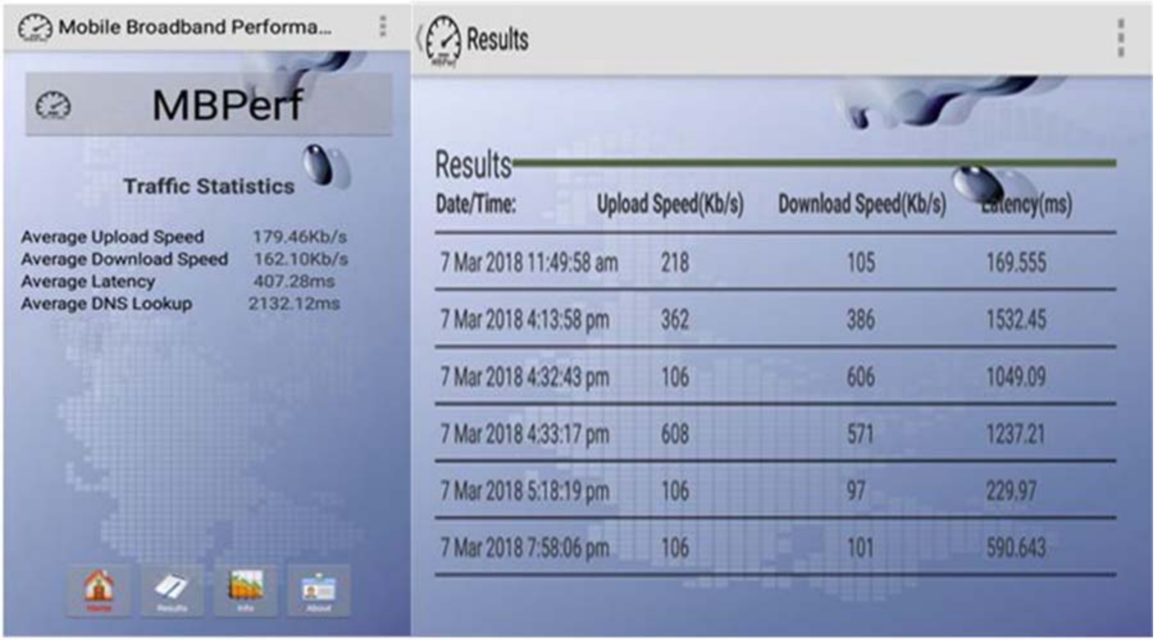

Figure 9: Home and results pages of MBPerf application (Akinlabi 2019).

factor on performance in South Africa, since latency to popular websites and services – as determined by both geographic location and Internet peering relationships – may significantly affect performance (Chetty et al. 2013a, 2013b).

In addition, only concerning latency does fixed-line broadband marginally outperfoms mobile broadband service. These were confirmed using the host-based measurements from MyBroadband presented in Figure 10.

Authors of (Bold and Davidson 2012) in 2018 published a report of the measurement of actual mobile broadband speeds and latency in 54 Low and Medium-Income Countries (LMICs). They collaborated with New America's Open Technology Institute to leverage Measurement Lab's (M-Lab's) dataset. The dataset examined a range of QoS metrics including median download and upload speeds measured in Megabits per second (Mbps) and latency measured in milliseconds (ms). M-Lab's Network Diagnostic Tool (NDT) was used in measuring the QoS metrics and collecting results. M-Lab's NDT is a widely used, open-source Internet measurement test which approximately collects 2 million NDT measurements every day from a diversity of locations and connection types, e.g. fixed and mobile.

Results for three (3) African countries – Egypt, South Africa and Nigeria are extracted and presented in Figures 11 and 12. Mobile broadband speeds and latencies peculiar to US/Canada and Europe are also presented for comparison with the result obtained in the Africa region. As Figures 11 and 12 illustrate, the slowest median download and upload speeds, as well as round trip latency, respectively were found in Egypt. The gaps between Africa and countries in North America and Europe are shown in Figure 13 for comparison. Median download speeds in the US and Canada were 4.76 Mbps, and 7.06 Mbps in Europe. Figure 14 shows the median latency results for each region. Again, much like the results for median download and upload speeds, mobile Internet users in Africa experience the largest delays – particularly compared with Europe.

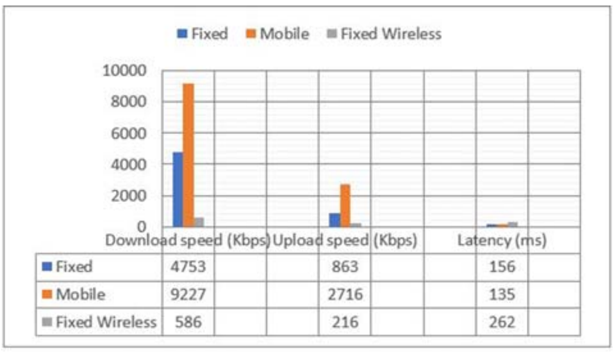

Figure 10: Fixed and mobile throughput and latency.
Source: RIA presentation of MyBroadband Data: 75,000 measurements in 2013 across South Africa

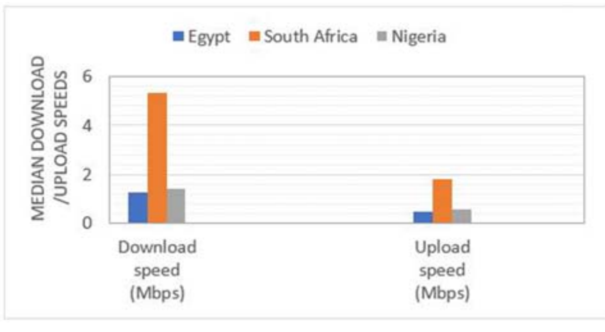

Figure 11: Median download and upload speeds in Egypt, South Africa and Nigeria (adapted from Woodhouse and Thakur 2018).

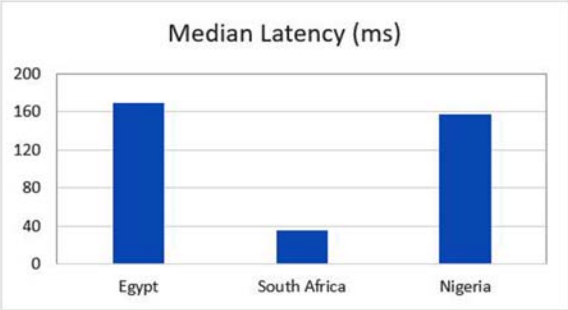

Figure 12: Median latency in Egypt, South Africa and Nigeria (adapted from Woodhouse and Thakur 2018).

With careful study of RIA's South Africa pilot project and other broadband as well as mobile broadband performance studies that have been undertaken in the UK, USA, Australia, India etc., two Researchers at The Federal University of Technology, Akure (FUTA) measured on a relatively small scale QoS offered by the four major MNOs to customers in two cities (Akure and Ibadan) of Nigeria. The research used a host and crowdsource-based approach. An Android QoS mobile application (MBPerf) was developed by the Researchers solely for this purpose (Dahunsi and Akinlabi 2019). It is important to note that the two approaches (router and host-based) employed in Africa are the popular and standardized methods used to measure fixed broadband and mobile broadband all over the world.

The result of the analyses showed that the MNOs did not meet the industry benchmark (as shown in Table 2) on 3G, though it outperforms 2G services. In addition, performance is highly variable (inconsistent and unstable) especially during the day and at peak times (between 7 and 11 pm), but greatly improves in the early hours of the morning (between 1 and 6 am). Furthermore, it was established as was the case with (Chetty et al. 2013a) that there are other factors other than speed such as time of the day and congestion that affect the overall performance that mobile broadband users get. A graphical summary of the overall average download and upload speeds and latency results aggregated for Akure and Ibadan is shown in Figure 15.

As RIA hopes to extend her measurements to other target countries in Africa (Chetty et al. 2013a), the authors also seek to increase their user base, coverage area and the number of metrics measured to ensure that the whole country is assessed.

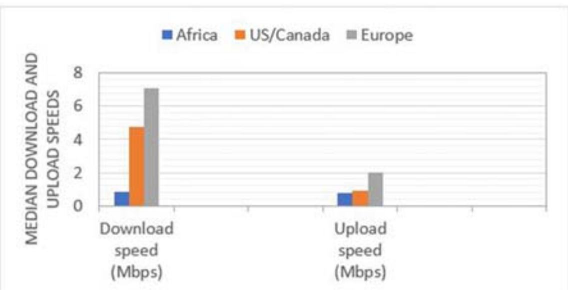

Figure 13: Median download and upload speeds (Mbps) by region (adapted from Bold and Davidson 2012).

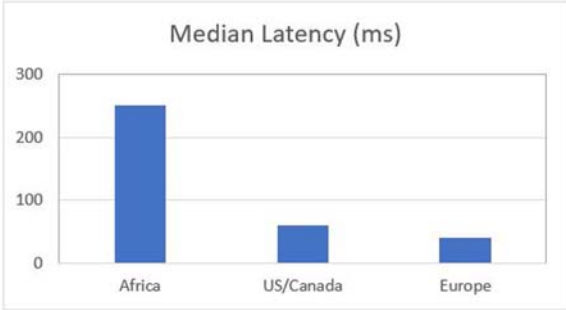

Figure 14: Median latency (ms) by region (adapted from Woodhouse and Thakur 2018).

Mobile broadband QoS measurements and analysis: lessons learnt, challenges faced

Based on this survey, some takeaways are offered for improving cellular network performance in developing countries. In addition, the various challenges that must be addressed when seeking to measure mobile broadband performance are also highlighted.

Lessons learnt

There are four major takeaways from previous studies relating to measuring broadband/mobile broadband performance in Nigeria (Dahunsi and Akinlabi 2019) and South Africa (Chetty et al. 2013a). Firstly, analysis of data collected via MBPerf and Speedtest applications in Nigeria and South Africa, respectively implied that the speeds delivered to mobile customers in both countries are less than the speeds advertised by the MNOs (Chetty et al. 2013a; Woodhouse and Thakur 2018; Dahunsi and Akinlabi 2019). Secondly, even though mobile broadband is more affordable than fixed broadband, its performance is highly variable (Chetty et al. 2013a; Woodhouse and Thakur 2018; Dahunsi and Akinlabi 2019) and inconsistent especially during the day and peak hours. Thirdly, unsatisfactory broadband speed is not the sole factor that limits the quality of broadband service in developing countries. Significant delays in delivering popular contents also have the capability of hindering QoS (Chetty et al. 2013a; Woodhouse and Thakur 2018). Lastly, significant variations in broadband speed for the same service can be recorded over time due to several complex factors relating to different measurement approaches (such as proximity of the test server to the

Figure 15: Mobile broadband throughput and latency.
Source: Dahunsi and Akinlabi (2019)

Table 2: Industry best standard values for QoS metrics.

S/N	QoS parameter	Industry benchmark
1	Latency (2G)	300–1000 ms
	Latency (3G)	100–500 ms
2	Download speed (2G)	100–400 Kbps
	Download speed (3G)	500–5000 Kbps
3	Upload speed (2G)	100–400 Kbps
	Upload speed (3G)	500–5000 Kbps

Source: Grigorik 2013

user, how the sample measurements were filtered and the amount of TCP connections used to run the speed tests) and measurement conditions (De Donato, Botta, and Pescapé 2014). For these aforementioned lessons, some important policy recommendations are proposed for developing countries and presented below.

A host-based measurement approach is recommended and advocated for the continued longitudinal study of mobile broadband performance in developing countries to help customers, MNOs, developers and regulators make informed decisions.

(1) Studies have shown that measurement of broadband performance is always beneficial to customers, MNOs and regulators (policymakers). For example, the BISmark measurements analyzed in (Chetty et al. 2013a) informed certain users they were not getting advertised speed. This is also the case with MBPerf dataset (Dahunsi and Akinlabi 2019). In addition, the host-based approach usually allows for broad coverage of the performance of many MNOs, since there is less effort required from the users (Chetty et al. 2013a) and it is also very cost-effective.
(2) It has been proven by (Chetty et al. 2013a) that broadband speed is not most times the main cause of poor, variable and inconsistent QoS. When the servers hosting particular services (or contents) are not closer to the users, consequently, latency becomes increased to the extent that the quality of connection becomes deteriorated and users are dissatisfied. Therefore, as regular calls for enhancing speeds in a country is made, regulators should also motivate private investors to build local facilities that will bring commonly used mobile services closer to the people. Regulators should also facilitate improved peering (interconnectivity) amongst the MNOs (Chetty et al. 2013a). With these in place, latency to popular websites and contents will be reduced to a large extent.
(3) Investment in local data centres and hosting will enhance the clossness of users to contents (Chetty et al. 2013a). It is quite unfortunate that most content developers in developing countries host their services on International servers as there are no local data centres and due to lack of uninterruptible power supply. Therefore, incentives (in form of an enabling environment) should be provided to corporations that serve users with popular mobile services for them to be able to cite hosting facilities and data centres in places that are nearer to the users (Chetty et al. 2013a).
(4) Governments of the developing countries should facilitate start-ups leading to investment in technology capable of producing local versions of popular services (Chetty et al. 2013a) like Dropbox, Facebook, Whastapp, etc. This would improve the technology market of the home-country as well as enhance the efficiency of these local services (Chetty et al. 2013a). Nigeria for instance has jumia.com, konga.com, etc., while South Africa has Kalahari.com; all akin to amazon.com in the US.
(5) Facilitate investment in fixed-line infrastructure: Fixed-line infrastructures in most developing countries are now in a dilapidated state. This is why mobile broadband is essentially their major means of accessing the Internet. But, even though mobile broadband outperforms fixed in terms of speed and price (Chetty et al. 2013a), the fixed infrastructure has higher reliability since it is less variable when compared to its mobile counterpart.
(6) Policymakers must develop responsive policies that will encourage operators to achieve the key performance indicators (KPIs) set by regulators for different QoS metrics. Regulators on their part should consult widely and be transparent in their oversight functions. In addition, they must be the custodian of reliable and open dataset on QoS for mobile broadband. Regulators can come up with a variety of punitive and non punitive approaches that will ease QoS investment. Lastly, operators need to provide consumers with transparent in-service offerings (Woodhouse and Thakur 2018).

Challenges of measuring mobile broadband performance in developing countries: Nigeria as a case study

Every effort to measure (monitor), analyse and report mobile broadband performance in any nation (especially the developing nations) of the world is bound to be faced with challenges. The challenges faced when performing mobile broadband measurements in Nigeria (Akinlabi 2019; Dahunsi and Akinlabi 2019) using a host-based and crowdsourcing approach and how these challenges wre addressed are explained in this section.

Diverse challenges were encountered during the effort to measure mobile broadband performance in two cities in Nigeria, which informed the measurement approach that can fit more appropriately to conditions in developing countries. Firstly, the size of the payload for MBPerf used for speed measurements was reduced to a hundred kilobyte due to the relatively high cost of data in Nigeria. Concluding on how appropriately measurements should be taken presents a trade-off: users' monthly data consumption increases with how frequent tests are carried-out but a high frequency testing schedule gives a robust data set. It is against this backdrop that tests carried out were configured to be carried out hourly on the mobile devices throughout data collection. Secondly, recruiting volunteers required much effort because volunteers find it hard to believe MBPerf did not collect their personal identifiable information. Some customers equally gave insufficient memory requirement as an excuse for not installing the application at all or uninstalling it after initial download and installation. Thirdly, some volunteers complained about putting on their device's GPS (location) (which was a requirement to be a volunteer) because it drains their battery faster. This is a very valid point because Nigeria's utility electricity supply is largely unavailable and erratic. Unfortunately, the constant off status of the GPS receiver prevented MBPerf from logging location information of volunteers at certain times. Hence, such measurements were inevitably discarded, since the location of users is one of the explanatory variables for MBPerf dataset. Finally, the design of MBPerf considered that data collection should not interrupt volunteers' connection to the Internet. The measurements were brief (a measurement cycle takes less than 2 min to complete) and were run as a background service. Having the volunteers initiate test themselves was discouraged. This may introduce bias into the performance effort as they might remember to run tests only when they are having issues with their networks. Furthermore, when volunteers do not remember to run tests, the number of data collected will be scanty thereby affecting the purpose of study which is to gather as many qualitative measurements as possible, which when analyzed will reveal a quantitatively correct impression of the performance offered by the participating MNOs.

Future directions

With the current oll out of advanced mobile broadband technologies (4G and 5G), there will be an upsurge in the speed of services offered by these technologies and the telecommunications market will become more complex. In this time, the focus of stakeholders will be geared towards designing improved methodologies for evaluating the performance of mobile broadband services. In addition, metrics such as availability and latency will now take the centre stage in how MNOs advertise and measure services. Similarly, reliability will become a more significant measure of merit as new frameworks for characterizing, measuring and evaluating mobile broadband QoS emerges. This is because the demand for reliable mobile broadband will increase as a wide range of services move to the Internet and the reliance on mobile broadband as a social economic infrastructure increases. It is therefore important for Researchers to start working on these issues.

Conclusion

Having detailed performance monitoring and analysis of today's ever-growing and complex mobile broadband networks is a very difficult task that requires the concerted efforts of all stakeholders. This is important in bringing about the adoption of universally acceptable tools and the execution of large-scale and long-term monitoring processes. No method or approach can be adjudged the best or the worst when it comes to network monitoring, as each approach comes with its own advantages and limitations. However, the ability to obtain fine-grained measurement results from diverse locations, devices and operators/ISPs, and is what determines the robustness of the monitoring effort. This survey has presented a detailed overview and comparison of the various approaches employed to date to measure the end-to-end performance of broadband networks. Several existing projects which produce different network services and tools were also explained and explored. General concepts such as mobile broadband, QoS, QoE and performance evaluation were dealt with to add more weight to the survey and to provide a fundamental understanding of this paper. Some very important policy recommendations based on lessons learnt from previous studies were also stated for the benefit of readers. It is recommended that more research is funded by both public (government) and private agencies so that the widespread interest amongst stakeholders to know how broadband networks perform is not quenched, since these studies would support the rise of new measurement approaches and platforms as well as optimize the existing testbeds.

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