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Speed isn't everything: a multi-criteria analysis of broadband access speeds in the UK

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Abstract:

In this paper, we demonstrate that there is more to consumer experience than just broadband access speed. We identify and describe a complex and dynamic set of interactions that occur between different factors that collectively determine consumer experience. We suggest that the relationship between broadband speed and consumer experience follows an inverted U-shape. Access speed is necessary to provide consumers with a good experience, but it is not sufficient. Based on our findings, a more nuanced understanding of the market for broadband Internet access products is outlined and a foundation for deriving valuable policy implications is developed. The results are of particular relevance for the ongoing universal service discussions in the UK and other countries.

Keywords: Internet Access, Broadband, QoS, QoE, Consumer Experience, Ofcom

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1. Introduction

For some time now, Usain Bolt, the 100m world record holder and regularly referred to as the world's fastest man, has advertised the broadband products of Virgin Media in the UK. His prominent role is a not so subtle attempt to emphasise how fast the company's broadband products are compared to those offered by their rivals like PlusNet, TalkTalk or Sky.[1] Indeed, the speed of Virgin's broadband network plays a key, perhaps central, role in the company's advertisement strategy.[2] Virgin Media is, perhaps surprisingly, not alone when promoting their products on the basis of speed. Its rivals also emphasis speed, often comparing how fast their new products are relative to their older (existing) ones.

Although average broadband speeds have increased over time (Ofcom, 2015a), most consumers are familiar with problems such as distorted audio signals or frozen video screens during Skype calls. Even though most consumers now enjoy broadband speeds that are considerably faster than the minimum mandated by Skype, the consumer experience is not what it should be. Similarly, many consumers watch movies through Netflix or Amazon Prime, and although average broadband speeds should be sufficient buffering delays and varying resolution qualities are relatively common. As the average broadband download speed in the UK is 29 Mbps (Ofcom, 2015b, p. 21), why does buffering or poor audio quality on Skype continue to occur?

The answer to this question is both simple and complex. It is simple in the sense that there is a gap between the download speed that the consumer subscribes to and what the Internet Service Provider (ISP) is able to deliver. Quite simply, the actual speeds delivered are on average less than the headline figure the customer subscribes to (Ofcom, 2016c). It is complex because even if the ISP can deliver the speed that the customer pays

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[1] According to Net Index, the average download speed for Virgin Media was 125.79 Mbps (as of August 2016) whereas the comparable figure for PlusNet was 57.93 Mbps, 37.60 Mbps for TalkTalk and 34.74 Mbps for Sky. Details of the speed test by ISP and city for the UK, which are regularly updated, can be found online at www.speedtest.net.

[2] Further details regarding the advertisements of Virgin Media can be found online at their website (www.virginmedia.com).

for, it cannot guarantee a good consumer experience. Consumer experience reflects the perceived quality of products and services (Bouch, Kuchinsky and Bhatti, 2000; Raake and Egger, 2014), and is a multi-dimensional concept that makes evaluations complex and involves several inter-related trade-offs. It is also shaped by the actions of, and the interactions between, the various players that collectively constitute the value chain that delivers a product or service to the final end user. The weakest link in the value chain, as determined by speed or service quality, shapes the perceived consumer experience. If, for example, content is delivered by a content provider with low resolution, the consumer experience is impinged upon irrespective of the quality of the other elements of the value chain. Furthermore, the ISP does not necessarily own or control the whole underlying infrastructure. The various parts of the infrastructure used to deliver services to consumers may be owned by different companies, and vary in terms of the bandwidth available and how they treat products and services such as voice-over-IP (VOIP) or over-the-top (OTT) services. The consumer experience may also vary depending on the digital literacy of the user.

With this in mind, the remainder of the paper explores the complexity of the broadband consumer experience. We do so through illustrating this complexity through reference to a series of products and services that are commonly accessed via broadband. Such an approach allows us to demonstrate how the various components of the value chain interact with one another to shape consumer experience.

In the following section, a brief overview of broadband is provided while our attention turns to broadband speeds in the UK in Section 3. In Section 4 we discuss consumer experience on the Internet before arguing that this is broader than speed in Section 5. Illustrations that demonstrate the complexity of consumer experience on the Internet are provided in Section 6, before the issues that arise are discussed in Section 7. Conclusions are drawn in Section 8, the final section of this paper.

2. Broadband

Socio-economic benefits

Over the last decade or so, an extensive literature has emerged that highlights the positive socio-economic benefits of broadband. Broadband increases economic output. One study of OECD member countries found that an increase in broadband penetration of 1% increased economic growth by 0.025% (Koutroumopis, 2009), while another, geographically broader analysis of 120 countries, found that a 10% increase in broadband penetration resulted in additional GDP per capita growth of 1.21% in developed and 1.38% in developing countries (Qiang, Rossotto and Kimura, 2009). Not only does this growth reflect the investment needed to build and operate broadband networks (Jackson, 2015; Singer, 2014), but also the innovative opportunities that emerge (Katz, 2012). Significantly, this innovative activity occurs across the whole economy (Cardona, Kretschmer and Strobel, 2013). In some countries the Internet has significantly contributed to economic growth; for example, the Internet contributed a third of Sweden's GDP growth between 2004 and 2009 and a fifth of the UK's over the same period (Economist Intelligence Unit, 2012b). It is, therefore, perhaps unsurprising that better broadband availability has also been found to be associated with higher levels of employment (Atasoy, 2013; Kolko, 2012; Singer, Caves and Koyfman, 2015).

Individuals also benefit from broadband. Not only can individuals become better informed through accessing online new sources,[3] but they can also benefit financially through, for example, purchasing and selling goods and services via the Internet.[4] Time can also be saved, through purchasing electronic goods and services as well as reduced commuting time. Research in Australia found these savings to be significant, and evident across many different types of households (Deloitte Access Economics, 2013). Of course, for individuals to be able to enjoy these benefits they require access to the Internet as well

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[3] For example, users can gain decision-relevant information by accessing vendor-independent portals that offer overviews over available products, evaluations of corresponding product qualities (typically based customer reviews) and price comparisons. For example, trivago.com offers a platform for hotel bookings based on a metasearch of specialized portals such as Booking.com or Expedia.com.

[4] Especially online marketplaces provide platforms for transactions between Internet users for all kinds of goods and services. A well-known example is Airbnb, a platform that is used by millions of people to rent (private) vacation homes.

as the means – device and IT literacy skills – to go online. Governments around the world have sought to address the barriers that many face to going online, with the various initiatives and strategies enacted coming together in a national broadband plan (International Telecommunication Union, 2015). These plans, while often broad in their scope, seek to improve access to broadband infrastructure through expanding infrastructure coverage in rural and remotes areas and provide companies and individuals alike with the skills necessary to maximise the advantages accruing from the Internet (Cisco and International Telecommunication Union, 2015; International Telecommunication Union, 2015; OECD, 2011).

Speed

An increasingly prominent strand of the literature on broadband focuses on speed. At one end of this debate, governments have set broadband speed targets. These targets vary considerably, reflecting the specific circumstances and existing infrastructural endowment of the country (see, for example, Economist Intelligence Unit, 2012a; OECD, 2011). Australia, for example, aims for 100 Mbps + Internet access to be available to 93% of homes, schools and businesses by 2021 while Luxembourg is aiming for every household to have access to broadband speeds of 1 Gbps by 2020 (OECD, 2011). Luxembourg's target stands in stark contrast with those of the European Union (EU). The EU has set a target of everyone having access to broadband at speeds of at least 30 Mbps by 2020, with at least half of households enjoying speeds of 100 Mbps or more.[5] A recent consultation regarding the EU's Digital Agenda does suggest, however, that there is widespread recognition that the targets should be more ambitious (European Commission, 2016).

There are economic benefits associated with faster broadband speeds. Analysing 33 OECD countries, Rohman and Bohlin (2014) found that doubling broadband speeds added an additional 0.3% to GDP growth between 2008 and 2010. Ericsson, Arthur D. Little and Chalmers University of Technology (2013) found that increases of 4 Mbps in OECD countries increased household incomes by $1200 a year, whereas increasing

[5] Further details of the European Union's Digital Agenda can be found online at ec.europa.eu

speeds by just 0.5 Mbps in Brazil, India and China resulted in household incomes rising by $800 a year.

Ezell, Atkinson, Castro and Ou (2009) argue that faster Internet access is necessary as it facilitates innovation. Next-generation broadband access should, according to them, ideally comprise of speeds of at least 50 Mbps for downloads and 20 Mbps for uploads. Innovators will draw on these increased speeds to develop new services and products, with Ezell, Atkinson, Castro and Ou (2009) identifying possibilities as diverse as video-conferencing, virtual sports, healthcare and grid computing.[6] This should not, however, be interpreted as suggesting that the impact of increased broadband speeds is limited to the ‘new economy’. Mack (2014), examining the relationship between broadband speeds and business creation in Ohio, found that speed had a positive impact on agricultural and rural businesses. In other words, the impact of speed can be found across the whole economy.

3. Broadband speeds in the UK

How fast are broadband speeds in the UK? For several years, Ofcom has published a report that charts the evolution of broadband speeds within the UK. The most recent one of these, from December 2015, highlights both the improvements that have occurred as well as the disparities that occur across the UK (Ofcom, 2015b). As can be seen from Table 1, the proportion of premises where superfast broadband is available has increased from 75% in 2014 to 83% in 2015 (Ofcom, 2015b). Superfast broadband is defined in the UK as broadband with download speeds of at least 30 Mbps (Ofcom, 2015b, p. 16). Average download speeds have also increased, from 54 Mbps in 2014 to 63 Mbps in 2015, reflecting the improvements in the network that have recently been undertaken.

[Insert Table 1 about here]

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[6] Four broad categories of next-generation broadband-enabled applications are identified by Ezell, Atkinson, Castro and Ou (2009), namely: consumer and business, society, health care and education and research.

Table 1 also highlights that superfast broadband coverage and speeds vary across the UK, with England enjoying significantly better coverage than the other nations. In contrast, average download speeds in Scotland are higher than elsewhere in the UK.

While average download speeds have increased, considerable variation remains. Across the whole of the UK, 8% of premises enjoy broadband connections of speeds of 10 Mbps or less (Ofcom, 2015b, p. 19). In rural areas, 48% of premises are connected by broadband lines with speeds of 10 Mbps or less; the corresponding figure for urban areas is just 4%.[7] Although superfast broadband download speeds are relatively fast at 63 Mbps the average download speed that takes into account all broadband products is considerably slower at just 29 Mbps (Ofcom, 2015b, p. 21). This lower UK average speed is due to the inclusion of premises with no or slower than 30 Mbps broadband connections.[8]

Riddlesden and Singleton (2014) suggest that the differences in broadband download speeds that they identify across the UK are engendering a new form of digital divide. This suggestion is supported, albeit tentatively, by Gijón, Whalley and Anderson (2016), who found that within Glasgow slower broadband speeds are associated with higher levels of deprivation. When these observations are combined with the socio-economic benefits of broadband noted above and the views of leading politicians that access to broadband is important today,[9] they vividly highlight the importance of broadband on the one hand and the significance of speed on the other. In late 2015 the government sought to address the issue of slow broadband speeds when it announced that everyone would have a legal right to request a 10 Mbps connection (Department for

[7] The uneven access to broadband lines is even worse when the threshold is reduced to 2 Mbps. Across the whole of the UK, 2% of premises are connected by lines of 2 Mbps or slower – 9% of rural premises enjoy broadband speeds of 2 Mbps or less, while the corresponding figure for urban areas is just 1% (Ofcom, 2015b, p. 19).

[8] Although Ofcom (2015b) does not provide a breakdown of premises by broadband speed for 2015, it does so for 2014. In 2014, 22% of premises did not have a fixed broadband connection with another 4% being connected by a line providing a download speed or less than 2 Mbps. 9% of premises had broadband providing download speeds of between 2 and 5 Mbps, 16% had access to broadband at download speeds between 5 to 10 Mbps and 23% of premises between 10 and 30 Mbps. Only 27% of premises were connected through superfast broadband, that is, had a connection of 30 Mbps or faster.

[9] Read (2016, p. 6) begins her report on broadband within the UK with a quote from the then Prime Minister, David Cameron, which states that: “Access to the internet shouldn’t be a luxury, it should be a right – absolutely fundamental to life in 21st century Britain”.

Culture, Media and Sport, 2015). While it was not clear from the announcement why the threshold had been set at 10 Mbps, the formal consultation document states that “10 Mbps enables full participation in our digital society – watching video on demand, listening to internet radio or streamed music, using social media, accessing Government services, shopping online and working from home” (Department for Culture, Media and Sport, 2016, p. 10). With a 10 Mbps connection, households could simultaneously consume in a range of online services,[10] and it is likely that they will consume more than was the case when they had a slower broadband connection (Ofcom, 2015b).

The proposed 10 Mbps threshold is higher than the UK’s existing universal service obligation (Feasey, 2016), though it is lower than the government’s current superfast broadband programme to deliver speeds of 24 Mbps or more to 95% of households by the end of 2017 (Rathbone, 2016). While Ofcom does suggest that faster broadband speeds are associated with a better consumer experience (Ofcom, 2015b, p. 29), it also notes that other factors do play a role. One important factor is located within the household, and is the technology that links the device to the broadband connection and thus both the access network and the wider Internet (Ofcom, 2015b). In addition, consumer experience may be affected by the increasingly complex nature of the value chain that provides goods and services online. In other words, faster broadband speeds do not necessarily result in an enhanced consumer experience.

4. Consumer experience on the Internet

In this section, we seek to understand the consumer’s experience of the Internet from two separate yet related perspectives. In the first sub-section below, the focus is on the theory that has been suggested to understand quality on the Internet while in the second sub-section the emphasis switches to understanding this from the perspective of the consumer. This second sub-section is, therefore, more practically orientated than the first.

[10] The universal service consultation document (Department for Culture, Media and Sport, 2016) draws heavily on Ofcom (2015b) to justify the 10 Mbps threshold. Ofcom (2015b, p. 27) suggests that with a 10 Mbps connection, a household could simultaneously consume basic web browsing (0.5 Mbps), video call + web browsing (1.5 Mbps), catch-up TV (2.0 Mbps) and high definition film streaming (6.0 Mbps). Of course, the multiple simultaneous consumption of high definition film streaming is not possible with a 10 Mbps connection (Ofcom, 2015b; Yiu and Fink, 2012).

In theory

A considerable body of work has emerged that seeks to theoretically understand 'quality' on the Internet.[11] In this literature consumer experience reflects the perceived 'aggregate quality' that consumers experience when using a particular service over the Internet. It is, however, necessary to disaggregate this experience as it is the outcome of a complex set of interactions between, broadly speaking, devices, infrastructure and services.[12]

To understand the complex set of interactions that occur, two widely accepted concepts are useful: Quality of Service (QoS) and Quality of Experience (QoE).[13] QoE is a holistic and subjective user-centric concept that focuses on the experience of a user when consuming application services.[14] The concept has increasingly gained importance as the industry recognises that network performance is a means to enable good consumer experience rather than an end in itself (see, for example, Bouch, Kuchinsky and Bhatti, 2000, p. 297; or Claffy and Clark, 2015, pp. 6f.). Increasingly optimization of the consumer experience is considered a major strategic objective, leading to QoE-driven network management strategies (Varela, Skorin-Kapov and Ebrahimi, 2014; Akamai, 2016a).[15]

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[11] A number of research articles provide an overview over the discussion over time. For an overview over the technical side of Internet quality in the context of network performance, see, for example, Claffy and Clark (2015). For early works emphasizing the relation between user experience and technical network performance, see for example Bouch, Kuchinsky and Bhatti (2000) or Bouch and Sasse (2001). For more recent state of the art discussions of Internet quality as perceived by users, see for example Moeller and Raake (2014). Also, standardization bodies like the ITU-T, ETSI and the IETF have been working on corresponding concepts (Varela, Skorin-Kapov and Ebrahimi, 2014, p. 87).

[12] Each of these broad areas can be further divided. For example, devices include tablets, computers (desktop and laptops), computer consoles and so forth while infrastructure includes networks of various geographical scales that may be comprised of fibre and/or copper/coaxial cables.

[13] For an overview of QoS and QoE, see, for example, Moeller and Raake (2014).

[14] QoE is defined as "the degree of delight or annoyance of a person whose experiencing involves an application, service, or system. It results from the person's evaluation of the fulfillment of his or her expectations and needs with respect to the utility and/or enjoyment in the light of the person's context, personality and current state" (Raake and Egger, 2014, p. 19).

[15] The popularity of Content Delivery Networks (CDNs) illustrates this development. CDN services are based on a decentralized content distribution approach and allow to provide end-to-end QoS levels customized to fit application-specific requirements in a way that user experience is optimized. An overview over the state of the art is given in Stocker, Smaragdakis, Lehr and Bauer (2016). In 2015, more than 60 % of the global Internet traffic has already been delivered over CDNs (Cisco, 2016, p. 3).

Although definitions vary, QoE is commonly understood as a broad concept. Factors relating to cognitive processing, context (for example, social, economic or technical context) and system (for example, network-related factors) are explicitly taken into account (Reiter, Brunnström, de Moor, Larabi, Pereira, You and Zgank, 2014). Essential for the consumer experience is the quality of data transmission. If poor, many application services simply cannot work satisfactorily. If very good, the performance of application services may still be impaired by other factors. Thus, a concept describing the quality of data transmission is crucial to understanding QoE, but can only shed light on part of the overall picture.

This can be illustrated by two simple examples. First, homogenous qualities of data transmission (that is, QoS) do not necessarily lead to homogenous levels of application performance. For example, user devices may vary significantly regarding CPU power such that application performance varies across devices. It is thus likely that user experience varies. Second, even if homogenous transmission qualities resulted in homogenous application performance, the user experience may still vary. This might be true for the obvious reason of heterogeneous user preferences but also in cases where user devices are heterogeneous. For example, the quality of headphones might lead to a different experience when consuming high definition music. Likewise, the resolution of the device's monitor may determine the experience in the consumption of high definition video content.

It is perhaps worth noting that QoS was originally understood as a somewhat user-centric concept similar to what is currently understood as QoE.[16] Over time, however, the focus shifted towards describing network performance (see, for example, BEREC 2010).[17] With the advent of the commercialization of the Internet and

[16] In their (superseded) recommendation ITU-T E.800 from 1994, the ITU (1994, p. 3; emphasis as in original document) defined QoS as "[T]he collective effect of service performance which determine[s] the degree of satisfaction of a *user* of the *service*." Also see, Varela, Skorin-Kapov and Ebrahimi (2014, pp. 87ff.)

[17] BEREC (2010, p. 18) emphasize the evolution in the understanding of QoS as describing network performance: "QoS is a concept that covers all aspects influencing the user's perception of the quality of the service. For voice services, for example, the QoS relates to the entire transmission path from mouth to ear […] The term QoS is often misunderstood as a synonym for network performance. Network performance is defined and observed as performance of a telecommunication network (or sections of a

concomitant innovation, application services with heterogeneous requirements regarding data transmission qualities emerged. The role of network performance for satisfactory performance of application services was recognized and led to an understanding of QoS as a network-centric concept based on measurable and thus objective parameters – for example, delay, jitter (variance of delay), packet loss rates or throughput (see, for example, Firoiu, Le Boudec, Towsley and Zhang, 2001, p. 1565).

And in practice

A recent study for Ofcom, the telecommunications regulator in the United Kingdom, explored the consumer experience within the context of broadband Internet services. Jigsaw (2016) argues that the consumer experience is composed of two components – service performance and customer services – that can be described through reference to a series of factors in two areas. These are:

- The stability of service performance: this refers to issues such as constant access speed, limited downtimes and the geographical availability of services.[18]
- Customer support: this refers to both the installation of the connection and associated repairs as well as related services like those provided through call centers.

Jigsaw (2016) argues that these two areas are interrelated and although they are complementary, substitution potentially exists between them. To a degree, good customer service could compensate for reduced service performance. Having this said, Jigsaw (2016) found that consumers consider service performance to be more important than customer services. A different perspective on the consumer experience can be found in Ofcom (2016a). This study found that poor decision-making by consumers is the result of the complex pricing strategies implemented by service providers, especially with respect to bundles and discounting.[19] Bundles, which can include third party application services

network) by using objective performance parameters. The relevant parameters are packet delay, jitter, packet loss, packet error (and throughput)".

[18] With regards to the geographical availability of services, a key issue here is, of course, whether the service is available in both urban and rural areas.

[19] For a discussion of bundling within the telecommunication industry see, for example, Mikkonen, Niskanen, Pynnönen and Hallikas (2015) or Pereira and Vareda (2013). While traditionally telecommunications contracts for end users did not include content-related components, the example of ESPN3 in the U.S. serves as an example for a bundled approach. End-users of partnering broadband access

like OTT, reflect the importance of contract-based vertical integration strategies within the value chain and further complicate the process of analysing the consumer experience.[20] Quite simply, the presence of bundling means that investigating consumer experience needs to take into account multiple services, devices and infrastructures in terms of how users experience and perceive services both separately and collectively.

5. There is more to consumer experience than just speed

The starting point here is a schematic illustration of consumer experience in Figure 1 (below). Figure 1 brings together the issues raised in the previous two sections to show how consumer experience is shaped by two sets of activities. The first of these, on the right-hand side of the diagram, are the customer services that the consumer requires and accesses. While important, especially when there may be problems with the physical connection, they are relatively limited in number compared to the left-hand side of the diagram that details those factors that depend on usage. We subsume these under the term service performance that can be divided into two broad areas that are related to the user on the one hand, and the system over which content and application services are delivered and consumed on the other. As can be observed from Figure 1, each can, in turn, be further sub-divided. Before each is recounted in turn below, it is necessary to remark that the colours of the boxes indicate the degree to which each component can be influenced by a typical access ISP.[21] This is important as subscribers typically turn to their access ISP to complain about unsatisfactory consumer experience. As can readily be observed, a lot of the factors determining consumer experience are beyond the direct influence of the access ISP.

[**Insert Figure 1 about here**]

ISPs get access to ESPN3 content and pay for this with their monthly fee (compare with, for example, Clark, Lehr and Bauer, 2016, pp. 349f.)

[20] For an overview of the bundles available to consumers within the UK, see, for example, the broadband pages of uSwitch, a price comparison website.

[21] Depending on the degree of vertical integration, the ISP's influence can vary.

Customer service

As noted above, customer service is neither related to the actual performance of application services or data transmission services nor to broadband speeds. It can thus be considered usage-independent. Instead, reliability, in a sense that maintenance and repairs are handled in an effective, supportive and timely manner, are important to consumers (Jigsaw, 2016, pp. 18ff./25ff.). In addition, billing and charging is perceived by consumers as important. Users interact with their ISP, but problems may occur if other market players are involved. For example, if an ISP purchases upstream products from Openreach that it, in turn, sells onto its own customers, co-ordination needs to occur between two sets of stakeholders, that is, between the customer and the ISP on the one hand and between the ISP and Openreach on the other. Co-ordinating between these stakeholders in the UK has been fraught with difficulties (Jigsaw, 2016, pp. 5/21f.), leading to Ofcom to recently assert that it needs to be improved (Ofcom 2016b). Even though customer service has no direct influence on the broadband speeds enjoyed by consumers, it does constitute an integral component of the overall experience and thus cannot be omitted from the discussion.

User

User preferences are heterogeneous. Digital literacy and the preference for specific types of content and application services shape how content and application services are perceived. There are considerable variations between consumers. As a result, different usage patterns, requirements and expectations emerge. In addition, user preferences are shaped by socio-economic, cultural, geographic and demographic characteristics (Reiter, Brunnström, de Moor, Larabi, Pereira, You and Zgank, 2014, pp. 56ff.). Further, user preferences may vary depending on the device that is used. Typically, Internet users have several types of devices that enable Internet access. Consumption patterns are differing depending on, for example, whether a smartphone or desktop PC with a high resolution monitor is used (Reiter, Brunnström, de Moor, Larabi, Pereira, You and Zgank, 2014; Sandvine, 2016b, pp. 6ff.). For selected fixed broadband networks in North America, a recent report by Sandvine (2016b, p. 3) finds that, per typical day, examined households use an average of 7.1 devices to connect to the Internet.[22]

Terminal Equipment

Terminal equipment such as routers, set-top boxes and user devices are typically part of a home network which is located downstream of the user-network-interface and thus not part of the access network. Nevertheless, performance in the home network by routers/modems or set-top boxes/SmartTVs might impede consumer experience as components might present barriers to exploit subscribed-to capacity usage. For example, this might be the case if routers are out-of-date (that is, hardware capabilities cannot match current requirements) or available wireless data rates are below subscribed-to access speeds. Furthermore, congestion in Local Area Networks (LAN) may impair the consumer experience. Imagine a situation in which multiple users share a single WiFi router in order to access the Internet. In general, the performance of wireless communications depends on a number of factors such as the distance between WiFi antenna and user device and structural conditions like the presence, number and composition of walls between the antenna and user device. Furthermore, if aggregate capacity requirements exceed available data rates, application performance and thus consumer experience decreases.

The variety of devices enabling Internet access has further implications on consumer experience. Devices range from 'traditional' personal computers, desktops and laptops, to gaming consoles, tablets and smartphones. Considerable variation can be found within each of these categories of access device, as well as between them. For example, desktops differ in terms of the size of their monitor, the speed of their CPU, quality of their graphics processor and how much memory (RAM) they contain.[23] Similarly, tablets and smartphones differ in terms of their screen size, CPU power,

[22] It was further found that more than 6% of examined households use more than 15 devices per day (Sandvine, 2016b, p. 3).

[23] For example, Dell is currently (August 2016) selling desktops in the UK that vary in terms of their processor chip (Pentium dual core; 4th generation core i3, i5 and i7; 6th generation core i3, i5 and i7), memory (4GB or 8GB +), storage (500GB or 1TB; hard disk or solid state), and graphics card (integrated or dedicated with 2GB + of memory) (Dell, 2016).

memory and so forth.[24] Thus, expectations and experience enjoyed by users will differ depending on the access device used. A user may, for example, be willing to watch a short clip on YouTube on their smartphone to address an immediate need but less willing to watch an hour long TV programme while using a mobile handset. In contrast, a user may prefer to engage in online shopping via a computer due to the larger screens and arguably easier search functions available online compared to mobile apps. The simultaneous use of multiple application services may impair application performance and may thus result in poor consumer experience.

Content and media

Consumer experience is naturally limited by the variety and available quality of content and applications. For example, in case of bundled subscriptions, media portals may not offer a full variety of movies or series.[25] Furthermore, the available video resolutions may not include high definition (HD) content.[26] Consumer experience is thus negatively affected by these constraints, irrespective of the actual network performance with which corresponding content is delivered. However, responding to current network conditions, available video resolution may be temporarily degraded by means of adaptive streaming protocols.[27] Indirectly affecting consumer experience are the requirements of different

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[24] Such differences can be illustrated with reference to the product line of leading smartphone suppliers like Apple and Samsung. If we take the former as an example, screen sizes vary from 1.52 inches (for example, Samsung E1200i) to 5.7 inches (for example, Samsung Galaxy Note 5) while the memory (storage), before the operating system is taken into account ranges from 4MB (for example, Samsung E1200i) to 64GB (for example, Samsung Galaxy 7). Also CPU power varies significantly from 156 MHz (for example, Samsung E1200i) to Octa core processors consisting of a 2.3 GHz quad unit and a 1.6 GHz quad unit (for example, Samsung Galaxy 7) (Samsung, 2016). Prices vary accordingly, with Apple selling the most recent version of its basic iPhone (iPhone SE) for $399 and its highest specification device (iPhone 6 S Plus) for $749 (Apple, 2016).

[25] Netflix bundles are not exhaustive, omitting many popular TV series and films. In addition, they also vary between countries as well – there are, for example, less than half as many films and TV series available in the UK bundle than there are in the US (Finder.com, 2016).

[26] This is emphasized by a recent case in the U.S. where OTT video service provider Netflix throttled video delivery for some of their mobile customers in an opaque way. Without knowledge or consent, customers of AT&T and Verizon were thus unable to consume high-resolution videos. Whereas Netflix claims that measures were taken on the basis of data caps, a member of an advocacy group pointed out that "most consumers that encounter video playback issues are likely to unfairly place the blame on their broadband providers" (Shepardson, 2016).

[27] Adaptive streaming is used by providers of video streaming services (for example, Netflix) in order to dynamically adapt sending rates and thus video resolutions to current network conditions. In particular, dynamic adaptive streaming over HTTP (DASH) is used by a number of video streaming services like

content and application services regarding the devices (that is, CPU, graphics processing, etc.) and specific QoS levels. Application services may further differ considerably regarding their usability, as well as QoS requirements. Not only do application services differ regarding required downstream and upstream data rates, they also differ regarding the timeliness and stability of packet delivery (see, for example, BEREC, 2014; Claffy and Clark, 2015).

Network Performance

Network performance and resulting QoS levels are crucial for application performance. The speed of end-to-end communications is explicitly addressed by the parameter throughput. The bigger the access pipe, the more data can be sent and received per second. Throughput, however, is a measure for the actual amount of data packets sent or received per second based on end-to-end communications. While a 'big pipe' is necessary for achieving high throughput rates, it is not sufficient.[28] In addition, other parameters like delay, jitter and packet-loss rates play an important role. Network performance serves as an input for Internet application services. It critically determines the performance of application services and thus consumer experience. As described in previous sections, QoS is an integral concept which is determined by the interaction of a number of service components. Two interacting sets of components can be subsumed under the heading of network capacities on the one hand and network management on the other. While available network capacities rather describe the maximum bounds of network performance, network management describes how these capacities are allocated and how scarcity situations are handled.

We divide physical network capacities into those that belong to the access and core network which are administered and operated by the access ISP and those that belong to the Internet. The access network begins upstream of the user-network-interface. End-to-end QoS levels are influenced by different factors and market players. Access ISPs

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Netflix (see, Adhikari et al., 2012). Lower video resolutions typically lead to losses in consumer experience (see, for example, Seufert et al., 2015, pp. 480f).

[28] End-to-end means, that communications between sender and receiver might require data packets to traverse several networks. Thus, although high access speeds may be available, end-to-end throughput rates and consumer experience may be very low.

provide consumers with Internet connectivity and have a broad influence on end-to-end QoS levels. Access capacities consumers subscribe to determine upper bounds for available data rates. Without sufficient bandwidth, consumers cannot make use of the full variety of content and application services available on today's Internet. Access bandwidth alone, however, is not sufficient for good consumer experience. Furthermore, network architecture, configuration and overbooking strategies at aggregation points impact available QoS levels.

Equally important is network management. Although, access products are based on flat fees, usage constraints such as monthly data caps might apply. Network resilience against states of congestion and the efficiency of capacity usage are determined by how data traffic is routed to and from consumers and how data packets are treated within the network. Traffic engineering (based on routing) and traffic management (based on prioritization or capacity reservation) determine the way data packets are handled.[29] In the UK, leading access ISPs comply to a 'Voluntary Industry Code of Practice of Traffic Management Transparency for Broadband Services' (Broadband UK, 2013). Accordingly, access ISPs transparently disclose the way they implement capacity allocations and resulting constraints for network usage particularly focusing on congestion management during periods of peak demands. While this information is valuable for consumers to understand the workings within the access network, it cannot provide the full picture of end-to-end QoS levels.

In order to ensure universal connectivity, that is, the ability of consumers to connect to content regardless of where it is located, access ISPs enter interconnection agreements. Different types of settlement-based or settlement-free interconnections with other ISPs, large content providers or providers of CDNs may be established.[30] In many cases, end-to-end delivery requires data packets to cross network borders. Hence, origination and

[29] While best effort principles imply that all data packets are treated equally, sophisticated mechanisms based on active traffic management may be used to mitigate the negative effects of network congestion. Active traffic management is based on QoS mechanisms based on prioritization between data packets or bandwidth capacity reservation. Typically, these mechanisms are used to provide differentiated service qualities (that is, QoS levels) taking into account heterogeneous application requirements.

[30] For an overview over Internet interconnection agreements, see, for example, Faratin, Clark, Bauer, Lehr, Gilmore and Berger (2008).

termination of data traffic are not handled by the same access ISP. Instead, other players are involved and access ISPs inevitably lose control over end-to-end QoS levels. Bargaining on the terms of interconnections (including capacities), as well as routing/traffic engineering and network management beyond the borders of the access ISPs play a crucial role in determining resulting QoS levels. For example, contractual inefficiencies and adverse routing strategies (for example, hot potato routing)[31] may impair end-to-end QoS levels of inter-provider traffic.

Recognizing this fact, in recent years access ISPs have made an effort to increase QoE for their consumers by reducing the distance data packets have to travel between source and destination. A seemingly effective strategy is to enter into direct interconnection agreements with fellow access ISPs and CDNs at geographically close interconnection points such as Internet Exchange Points (IXPs). Through this strategy, the number of players involved in end-to-end packet delivery is reduced. In particular, interconnections with CDNs are popular in order to increase consumer experience. More than 40% of today's Internet traffic and more than 60% of video traffic are already delivered via CDNs (Cisco, 2016, p.18). CDN strategies play a central role in QoE optimization as content and applications are cached in close proximity to consumers. There are different strategies for ISPs to exploit potentials of enhanced QoS levels based on CDN service provision. Recently, a number of ISPs have entered strategic alliances with CDN providers in order to gain more control over QoS levels and to enhance the consumer experience (see, for example, Frank, Poese, Lin, Smaragdakis, Feldmann, Maggs, Rake, Uhlig and Weber, 2012). CDNs typically make use of a number of mechanisms – for example, adaptive streaming, prefetching or front end optimization – that constitute traffic management mechanisms complementary to basic Internet packet delivery while still complying with best effort principles (see, for example, Knieps and Stocker, 2016).

[31] The hot potato strategy basically describes an opportunistic routing behavior followed by most ISPs. In order to shift the cost of packet delivery to other ISPs, ISPs try to get rid of those data packets that are not terminated within their own network at the nearest interconnection point. See, for example, Faratin, Clark, Bauer, Lehr, Gilmore and Berger (2008).

While the descriptions in this section have demonstrated that, in an ecosystem as complex as the Internet, access speed is but one component in a complex and evolving mix of interacting components. In order to gain insight into the importance of service performance, the impact of QoS levels on application performance shall be briefly described in the following section.

6. Illustrations

In this section we shall demonstrate how the issues raised in the previous section affect a range of typical online activities. This is undertaken through a common analytical framework that highlights how each service is, for example, affected by jitter or requires high throughput.

Email and browsing the Internet

Application services like browsing the web or sending and receiving emails are rather tolerant regarding the timeliness of packet delivery. High throughput rates and low packet loss rates lead to shorter loading times of websites and thus increase the consumer experience.

[Insert Table 2 about here]

Cloud storage and file sharing

A trend towards backup solutions and data storage in the cloud is observable. Application services like Dropbox, Apple iCloud, Amazon Cloud Drive or Google Drive allow users to eliminate the risk of data losses due to hardware failure. Furthermore, services ensuring synchronization between a number of devices may be provided and data stored in the cloud can be accessed from everywhere. Other application services like BitTorrent allow file sharing. The larger the files that are downloaded or exchanged, the higher are required data rates. Applications are rather tolerant regarding the timeliness of packet delivery. In order to ensure completeness of transferred data, packet losses in a sense of information losses must be avoided.

[Insert Table 3 about here]

VoIP and video conferencing

Bidirectional real-time OTT application services like voice over IP (VoIP) or video teleconferences are highly sensitive to distortions in QoS levels. Regarding requirements towards data rates, bidirectional real-time communications services require rather symmetric up- and downstream data rates. For voice calls, Skype recommends 100kbps upstream and downstream rates. For video calls, recommendations vary depending on video resolution and the number of people taking part in the conversation. For standard video calls between two devices, data rates of 500 kbps are recommended while for HD video calls 1.5 Mbps is recommended. For group calls, asymmetric data rates of up to 8Mbps downstream and 512 kbps upstream are recommended (Skype, 2016). Google Hangout recommends data rates of 2.6 Mbps for video calls between two devices. For group calls, upstream data rates of 2.6 Mbps are recommended. Depending on the number of communicating devices involved, downstream data rates of up to 4 Mbps are recommended (Google, 2016a). Apple describes minimum data rates of 1 Mbps in order to use their FaceTime HD video call service (Apple, 2016). Although requirements regarding data rates vary, voice and video calls are rather homogenous regarding their sensitivity to delay, jitter and packet loss rates. In order to enable good experience, one-way delay times should be below 150 ms (International Telecommunication Union, 2001, p.8).

[Insert Table 4 about here]

Media streaming

Media streaming services, in particular OTT video streaming services like Netflix, YouTube or Amazon Prime are very popular and account for a substantial proportion of global Internet traffic (Sandvine 2016a, p. 4; Cisco 2016, pp. 3/17). But what about the experience of using these services? Imagine a consumer streams a high definition movie from a server via a congested link. State of the art streaming uses adaptive streaming technology, that is, video resolution dynamically adapts to the network conditions being experienced.[32] Netflix offers a number of different video resolutions. For video streams in

[32] For example, based on average values over the last 30 days, Google transparently provides information on the quality of video delivery on a typical day. Giving information for each hour of day, the share of videos delivered in HD, SD and LD (low definition) is illustrated. See Google (2016c).

standard definition (SD) resolution 3 Mbps of downstream data rates are recommended. 5 Mbps are recommended for high definition (HD) videos and at least 25 Mbps for Ultra HD videos (Netflix, 2016).

[Insert Table 5 about here]

In contrast, Amazon Prime Video recommends 900 kbps for SD videos and 3.5 Mbps for HD videos (Amazon, 2016). BBC recommends at least 2.75 Mbps downstream data rates for watching HD videos via its iPlayer application (BBC, 2016). Regarding live encoding, YouTube differentiates between five different resolutions (240p, 360p, 480p, 720p, 1080p) and an extra 60 frames per second option. Bandwidth requirements vary between 300kbps and 9Mbps (Google, 2016b). Inherent to video streaming services is that asymmetric data rates result. Rather small requests result in low upload rates. The bulk of data travels downstream towards consumers. In case of congestion, adaptive streaming reacts to decreasing throughput rates by lowering video resolution. Further, packet losses impair application performance. While buffering may mitigate some distortions, application performance and thus consumer experience will be substantially degraded.

7. Discussion

In the previous sections we have focused on consumer experience. We have shown that consumer experience is shaped by a complex and dynamic set of interactions that occur between the online activity being undertaken, the underlying infrastructure and the user. As a result, it is difficult, if not impossible, to categorically identify the factors that constrain or impair consumer experience. As is evident from recent figures by Ofcom, many factors contribute, sometimes simultaneously, to the complaints that users make regarding their broadband provision (Ofcom, 2016d).[33]

[33] Since the first quarter of 2011, there have, relatively speaking been more complaints associated with broadband provision than with mobile, fixed line and pay-tv services (Ofcom, 2016d, p. 16). In the first quarter of 2016, the broadband services offered by EE received the most complaints, with the complaints relating to “faults, service and provision issues, complaints handling and issues with billing, pricing and charges” (Ofcom, 2016d, p.18).

Given the uncertain determinants of consumer experience, what role does speed play? At its most basic, (very) slow broadband download speeds will be frustrating for consumers, causing delays in the accomplishment of some tasks and making other online activities effectively impossible to achieve. This suggests that increasing broadband download speeds will positively affect the consumer experience. To a degree, this is likely to be the case. Providing a broadband connection where none previously existed, or replacing a slow broadband connection with a faster one, should improve consumer experience. Quite simply, not only will online tasks be accomplished more quickly but also a wider array of tasks than previously was the case will now be possible.

But is the relationship between broadband speed and consumer experience linear? That is, does ever increasing broadband speeds result in continuously improving consumer experience? We suggest that the relationship between broadband speed and consumer experience follows an inverted U-shape. As broadband speeds initially improve, the consumer experience will improve as users are able to undertake more online but as the factors noted in Sections 4 to 6 come to the fore the relationship changes.

A key factor in shaping this relationship is the nature of the value chain – for the relationship to be linear, speeds across the whole chain will need to be aligned and increase in unison.[34] Among other things, this would require orchestrated investment strategies and more or less consistent network policies. In practice, this does not happen. As a consequence, an important implication emerges: access speed is necessary to provide consumers with a good experience, but it is not sufficient.

It can be reasonably assumed that expectations of those consumers who subscribe to broadband plans containing high access speeds, increase monotonically with the access speed they subscribe to. User preferences are revealed in a self-selection process – consumers are willing to pay more for higher access speeds. The motivation for the higher willingness to pay may be the expectation that higher access speeds provides additional utility. As noted in previous sections, the relationship between higher access

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[34] For a more detailed discussion of different scenarios in which such speeds are aligned or not, see Bauer and Lehr (2015, ch. 3).

speeds and increased utility may be true as long as access speeds constitute the weakest link in the delivery chain. For a range of consumer preferences and demand patterns, more content and application services can be simultaneously used with satisfactory application performance and consumer experience. However, the monotone relationship between access speeds and consumer experience breaks down if access speeds reach a critical threshold that require other network components and contractual arrangements to adapt. As these adaptions occur, consumer experience does not increase but instead begins to decline as customer expectations are not met.

For consumers who described their broadband connection as being "less than good", Ofcom found that in at least 14% of cases the cause was located inside the consumer's premises (Ofcom, 2015b, p. 53). Within a household, many users rely on WiFi to connect their devices to the Internet via a fixed broadband connection. The unsatisfactory nature of WiFi has been found to play a role in those broadband connections described as being "less than good" by consumers (Ofcom, 2015b, p. 30).[35]

Outside the household, the value chain is complex. It involves a range of infrastructure providers, who may use different technologies and traffic management strategies in their networks, as well as CDNs and providers of Internet-based content and application services. The consumer's experience may, however, be negatively affected by each component of the value chain that provides a particular service to the end user.[36] Ofcom (2015b) identifies where across the value chain performance issues are located for a range of services. Interestingly, for those services that they identify as being typically used by both consumers and small and medium sized enterprises, they find that the Internet and the home network play a relatively small role as a source of performance issues. Instead, the majority of issues arise from the access network or the ISP core, with

[35] Ofcom went as far as making freely available an app to check the quality of WiFi connections.

[36] Evidence for impaired QoE due to uncoordinated efforts between market players is (indirectly) shown by data provided by Akamai, the world's leading provider of commercial CDN services. On their website, they give information on both average delivery speeds and average peak delivery speeds in the UK. Data show that average connection speeds are 14.936 Mbps, while average peak connection speeds are given at 60.962 Mbps (Akamai, 2016b). This shows that on average, available speeds are only 24,5% of the peak average speeds which should be close to what the customers are paying for. Further, it must be noted that these numbers take into account the set of optimization techniques that are applied by Akamai and which are not available for all non-CDN traffic. Similar measures for a large amount of non-CDN traffic can thus be expected to give even lower average connection speeds.

the former being more prominent than the latter (Ofcom, 2015b, p. 55). In contrast, when services typically used just by small and medium sized enterprises are examined, the Internet plays a more significant role as a sources of issues affecting the performance of applications based on the cloud or video conferencing (Ofcom, 2015b, p.55). In each case, the largest source of problems remains the access network.

Unfortunately it is unclear from Ofcom (2015b) what role speed plays in someone deciding that their broadband experience is unsatisfactory. Thus, while improving the access network through, say, replacing copper with fibre or implementing g.fast will improve speeds, it does not necessarily follow that consumers will become happier with their faster broadband connection. The presence of a faster broadband connection may raise consumer expectations, and thus the likelihood of them complaining at some point in the future.

The issue of traffic management by access ISPs has been the source of wide concern among the Internet community for the last decade and has been intensively discussed in the course of the network neutrality debate (see, for example, Wu, 2003; Kraemer, Wiewiorra and Weinhardt, 2013; Knieps and Stocker, 2015/2016). Measures taken by the access ISP, for example, ad hoc usage constraints based on traffic (de-)prioritization in order to mitigate congestion, differ between providers and may have different effects on consumer experience. In general, practices may not be well understood by Internet users and deviations from disclosed methods may be hard to detect.[37] In the UK, Ofcom (2013) as well as major ISPs have addressed this issue. For example, as outlined in Section 5, major ISPs in the UK have signed an industry code that specifies best practices in the communication of information regarding their traffic management practices. On a European level, a network neutrality regulation introducing a set of rules specifying traffic management practices for Internet access services was recently enshrined (European Parliament and Council, 2015).

[37] In a study prepared for Ofcom, Kantar Media (2013) explored potentials how to effectively communicate traffic management information to consumers. In their study, they found that only 9 per cent of consumers were aware of their ISP's traffic management practices. Further, only 6 per cent of consumers claimed to take into account ISPs' traffic management practices into future purchasing decision (Kantar Media, 2013, p. 28).

If the customer does complain, the complex nature of the value chain delivering the service raises the following question: who is to blame? The problems could emanate from the use of WiFi within the premise to connect devices to the Internet, or could be the result of inadequate infrastructure at some point. Alternatively, problems may arise because of insufficient bandwidth linking a website to the Internet. If the exact location of the problem(s) being experienced by the consumer is to be determined, then network performance measurement across the whole value chain delivering a particular service is needed. While this is technically possible, dynamic routing as well as traffic management techniques may make this quite challenging to undertake in practice. Moreover, as access speeds increase consumer expectations may rise to the point that they are unreasonable, in part, because consumers do not fully understand how the Internet is structured and operates. There is, as a consequence, a danger that a 'cycle of blame' will emerge where consumers blame one party or another, perhaps because the contact details for consumer support of their access ISP are more readily available than those of a content provider.[38]

8. Conclusion

The Internet is highly dynamic and rapidly evolving. With the increasing complexity of the Internet ecosystem and emerging trends like the Internet of Things, the number of devices connected to the Internet and demand for bandwidth capacities are continuously increasing. Within this dynamic and changing context, the role of broadband access speeds in enabling high levels of consumer experience is often emphasized. In this paper, we demonstrated that consumer experience is made up of a myriad of interacting factors that are only partially under the control of the access ISP. While access speeds might be used as a proxy to indicate the potential of Internet access products, they must not be confused as an indicator for consumer experience. In fact, there is more to consumer experience than just broadband access speed. Our analysis has suggested a more nuanced approach to understanding customer experiences and lays the foundation for policy recommendations.

[38] We use the term 'cycle of blame' here as used in a recent presentation by MIT's David Clark describing user complaint behaviour in the Internet (see, Clark, 2016).

If we return to the 10 Mbps universal service obligation recommendation in the UK, such a suggestion will clearly improve consumer experience where no Internet access previously occurred. The delivery of such access speeds will, however, be affected by the composition of the value chain delivering specific services. As a consequence, consumers may find it frustrating to use some services, such as VoIP and video conferencing, especially when WiFi is a component of the delivery value chain or multiple services are being used simultaneously. This suggests that if consumers are to enjoy a discernible improvement in their experience, then the target speed needs to be substantially raised.

While the use of QoE has been advantageous, it could be improved in two ways. Firstly, the concepts integral to QoE would benefit from being more clearly articulated and defined. This would, secondly, facilitate improvements in how these components are measured. In addition, although our analysis has sought to disentangle the factors that shape consumer experience, empirical research is required to explore how the various components interact with one another and thus shape the consumer's experience. Not only should this empirical research focus on those parts of the service delivery value chain outside the premise, but it would also take into account 'internal' factors and the number of simultaneous users as well.

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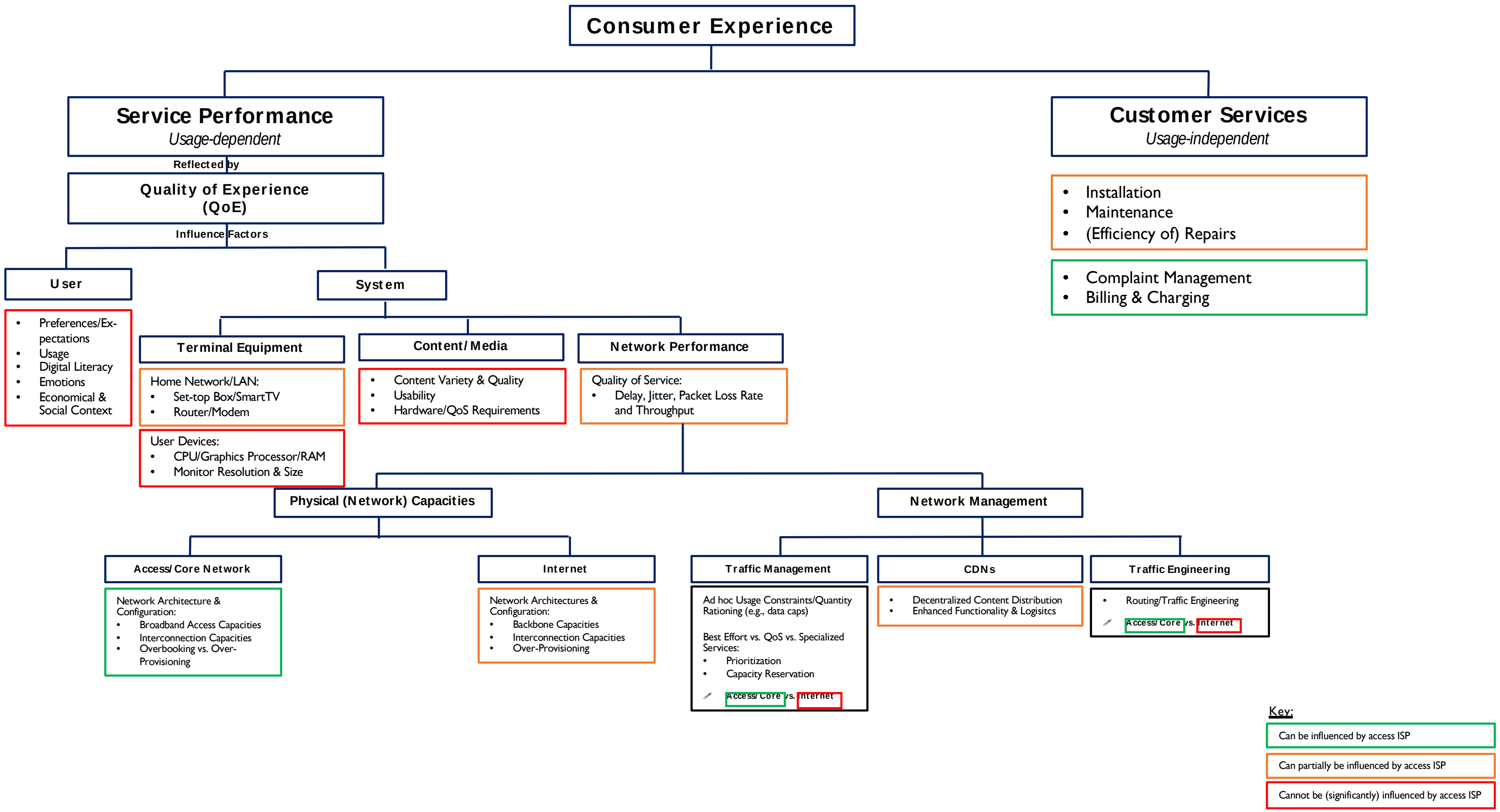
Table 1: Coverage and speed of superfast broadband

	Coverage of superfast broadband, % premises		Average download speed of superfast broadband, Mbit/s	
	2015	2014	2015	2014
UK	83	75	63	54
England	84	77	63	56
N Ireland	77	77	56	50
Scotland	73	61	67	54
Wales	79	55	59	52

Source: Ofcom (2015b)

Figure 1: The Many Dimensions of Consumer Experience



Source: Authors

Table 2: Email and browsing

Application Service	Throughput		Delay	Jitter	Packet Loss Rate
	Downstream	Upstream			
Browsing the Web (text/media)	++/+++	-	++	-	+++
Email	-	-	-	-	-

Notes: - = less important; +++ = very important
Source: based on Stocker (2015); BEREC (2014)

Table 3: Cloud storage and file sharing

Application Service	Throughput		Delay	Jitter	Packet Loss/Information Loss Rate
	Downstream	Upstream			
Cloud Storage / File Sharing	+++	++/+++	+	-	+++

Notes: - = less important; +++ = very important
Source: based on Stocker (2015); BEREC (2014); Gonsalves and Bharadwaj (2009)

Table 4: VOIP and video conferencing

Application Service	Throughput		Delay	Jitter	Packet Loss Rate
	Downstream	Upstream			
Voice over IP	+	+	+++	+++	+
Video Teleconferences	+++	+++	+++	+++	+/++

Notes: - = less important; +++ = very important
Source: based on Stocker (2015); BEREC (2014); International Telecommunication Union (2001)

Table 5: Media streaming

Application Service	Throughput		Delay	Jitter	Packet Loss Rate
	Downstream	Upstream			
Video Streaming	+++	-	+	-	+

Notes: - = less important; +++ = very important
Source: based on Stocker (2015); BEREC (2014)