Telecommunications Policy 42 (2018) 1–14

Contents lists available at ScienceDirect

Telecommunications Policy

journal homepage: www.elsevier.com/locate/telpol

Speed isn't everything: A multi-criteria analysis of the broadband consumer experience in the UK

Volker Stocker[a,*], Jason Whalley[b,c]

[a] Abteilung für Netzökonomie, Wettbewerbsökonomie und Verkehrswissenschaft, University of Freiburg, Freiburg, Germany
[b] Newcastle Business School, Northumbria University, Newcastle, UK
[c] TELECOM École de Management, Institut Mines and Telecoms, Évry, France

A R T I C L E I N F O

Keywords:
Internet access
Broadband
QoS
QoE
Consumer experience
Ofcom

A B S T R A C T

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.

1. Introduction

For some time now, Usain Bolt, the 100 m 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 role in the company's advertisement strategy. 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 significantly over time (Ofcom, 2015a, 2016d), 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 access 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 access speeds should be sufficient, buffering delays and varying resolution qualities are relatively common. As the average broadband download speed in the UK is 37 Mbps (Ofcom, 2016e, p. 4), 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. It is complex because even if the ISP can deliver the speed that the customer pays for, it cannot guarantee a good consumer experience. Consumer experience reflects the perceived quality of products and services (Bouch, Kuchinsky, & Bhatti, 2000; Raake & Egger, 2014), and is a multi-dimensional concept

* Corresponding author.
E-mail addresses: volker.stocker@vwl.uni-freiburg.de (V. Stocker), jason.whalley@northumbria.ac.uk (J. Whalley).

[1] In November 2016, according to speedtest.net, the top 10% download speed (that is, the 90th percentile) for Virgin Media was 161.33 Mbps whereas the comparable figure for BT was 63.23 Mbps. The figures for Plusnet, TalkTalk and Sky were 59.53 Mbps, 37.57 Mbps and 36.27 Mbps respectively (Ookla, 2016).

http://dx.doi.org/10.1016/j.telpol.2017.06.001
Received 12 November 2016; Received in revised form 29 May 2017; Accepted 3 June 2017
Available online 26 July 2017
0308-5961/

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. Additionally, the consumer experience may also vary depending on the devices that are used to access the Internet, the configuration of home networks and 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 by 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. We explore the relationship between Quality of Service (QoS) and Quality of Experience (QoE), demonstrating how customer experience and speed display an inverted U-shaped relationship. In the following section, a brief overview of the advantages associated with 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 the 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. Why broadband is important

2.1. 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, & Kimura, 2009). 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 (Singer, Caves, & Koyfman, 2015). Additionally, it has been associated with improvements in healthcare as well as the management of natural resources and resiliency to climate change (Broadband Commission for Sustainable Development, 2016; Mölleryd, 2015).

Furthermore, individuals may also benefit directly from broadband. Not only can individuals become better informed through accessing online new sources, but they can also benefit financially through, for example, purchasing and selling goods and services via the Internet. Time can also be saved, through purchasing electronic goods and services as well as reduced commuting time. Of course, for individuals to be able to enjoy these benefits they require access to the Internet as well as the means – device and IT skills – to go online. There are, all things considered, wide-ranging socio-economic benefits to be derived from broadband adoption.

2.2. 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). Focusing on peak downstream data rates, Australia aims for 50 Mbps Internet access to be available to 90% of fixed line premises, and 25 Mbps to all premises as soon as possible (Government of Australia, 2016). New Zealand follows a more differentiated, multi-tiered, approach. By the end of 2024, the Ultra-Fast Broadband Initiative (UFB) aims to provide fibre-based Internet access with peak speeds typically ranging from 100 Mbps to 1 Gbps to 84% of New Zealanders (Ministry of Business, Innovation & Employment, 2017). In addition, the Rural Broadband Initiative (RBI) aims at ensuring the availability of 50 Mbps Internet access to 99% of New Zealanders, and 10 Mbps to the remaining 1%, by 2025 (Adams, 2015). More ambitious goals are being pursued by Luxembourg, which 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) more generally. The EU has set a target of everyone having access to broadband at speeds of at least 100 Mbps (upgradable to Gbps speeds) by 2025 (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 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) emphasize the role of faster Internet access in facilitating innovation in the Internet ecosystem. Innovators are expected to draw on high-capacity next-generation broadband access to develop new services and products. Innovations related to services as diverse as HD video-conferencing, cloud computing, virtual reality, and the Internet of

Table 1
Coverage of superfast broadband and average broadband speeds.

	Coverage of superfast broadband, % premises		Average download speed of broadband, Mbps		Average upload speed of broadband, Mbps	
	2016	2015	2016	2015	2016	2015
UK	89	83	37	29	4	4
England	90	84	38	30	4	4
N Ireland	83	77	34	28	4	4
Scotland	83	73	35	27	4	3
Wales	85	79	29	23	3	3

Source: Ofcom (2016e, p. 4).

Things (IoT) are facilitated through the high data rates that broadband Internet access provides (European Commission, 2016; WIK, Deloitte and IDATE, 2016). 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 2016, highlights both the improvements as well as the disparities that have occurred across the UK (Ofcom, 2016e). As can be seen from Table 1, the proportion of premises where superfast broadband is available has increased from 83% in 2015 to 89% in 2016.[2] Reflecting the improvements in the network that have recently been undertaken by operators, average download speeds of superfast broadband have increased from 65 Mbps in 2015 to 74 Mbps in 2016 (Ofcom, 2016e, pp. 1/11f.).

Table 1 also highlights that superfast broadband coverage and general broadband speeds vary across the UK, with England enjoying significantly better coverage than the other nations. While average download speeds have increased, considerable variation remains. Across the whole of the UK, 5% of premises enjoy broadband connections of speeds of 10 Mbps or less (Ofcom, 2016e, p. 11). In rural areas, 25% of premises are connected by broadband lines with speeds of 10 Mbps or less; the corresponding figure for urban areas is just 2% (Ofcom, 2016e, p. 19). Although superfast broadband download speeds are relatively fast at 74 Mbps, the average download speed that takes into account all broadband products is considerably slower at just 37 Mbps. While this lower UK average speed is due to the inclusion of premises with no or slower than 30 Mbps broadband connections, it is arguably remarkable that average upload speeds have remained static at 8 Mbps for superfast and 4 Mbps for all broadband products (Ofcom, 2016e, p. 1).

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 is that access to broadband is important today,[3] they vividly highlight the essentiality 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 Culture, Media and Sport, 2015).[4]

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 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 play a role.

4. Consumer experience on the internet

Consumer experience may be affected by the increasingly complex nature of the value chain that provides online goods and services. In other words, faster broadband speeds do not necessarily result in an enhanced consumer experience. In this section, we seek to understand consumer experience on the Internet from two separate yet related perspectives. In the first sub-section below, the

[2] Superfast broadband is a term defined by Ofcom, the UK's regulator, as broadband with download speeds of at least 30 Mbps (Ofcom, 2015b, p. 16). While "superfast" must not be confused with specific high-capacity or gigabit fibre deployments, the following analysis will follow Ofcom's definition.

[3] 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".

[4] While the discussion of the introduction of a universal service regulation is beyond our remit, some observations can be made. 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 & Fink, 2012).

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.

In theory …

A considerable body of work has emerged that seeks to theoretically understand 'quality' on the Internet.[5] 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. Each of these broad areas can be further divided. For example, devices include tablets, computers (desktop and laptops) and computer consoles while infrastructure includes networks of various geographical scales that may be comprised of fibre and/or copper/coaxial cables and thus may have heterogeneous performance characteristics.

To understand the complex set of interactions that occur, two widely accepted concepts are useful: Quality of Service (QoS) and Quality of Experience (QoE) – see, for example Möller and Raake (2014) or Struble (2016) for an overview of these two concepts. QoS was originally understood as rather a broad user-centric concept similar to what is currently understood as QoE.[6] As Internet innovation led to the emergence of content and application services with heterogeneous data transmission requirements, the role of network performance for satisfactory performance of application services was recognized. Related developments led to an understanding of QoS as a network-centric concept based on measurable and thus objective parameters – for example, delay, jitter, packet loss rates or throughput (see, for example, Firoiu, Le Boudec, Towsley, & Zhang, 2002, p. 1565, or BEREC, 2010, p. 18). While the focus of QoS has thus shifted significantly, it is essentially linked to the broader concept of QoE.

QoE is a holistic and subjective user-centric concept that focuses on the experience of a user when consuming content and applications online. Although definitions vary, it is commonly understood as a broad concept that takes into account factors relating to cognitive processing, context (for example, social, economic or technical context) and system (for example, network-related factors) (Reiter et al., 2014). QoE can be 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 fulfilment 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 & Egger, 2014, p. 19). Over the years, the concept has increasingly gained importance as the industry has recognised that network performance (that is, QoS) is a means to enable good consumer experience rather than an end in itself (see, for example, Claffy & Clark, 2015, pp. 6f. or; Claffy, Clark, Bauer, & Dhamdhere, 2016).

The concepts of QoS and QoE are concatenated: QoS is an essential input for QoE and thus consumer experience. Poor QoS levels may lead to the unsatisfactory performance of QoS sensitive content and applications and bad QoE for end users. If very good, application performance and consumer experience may still be impaired by other factors. This can be illustrated by two simple examples. Firstly, high and homogenous qualities of data transmission 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, therefore, likely that QoE and consumer experience will accordingly vary. Secondly, even if homogenous QoS levels resulted in homogenous application performance, the QoE can 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 may lead to different experiences when consuming high-definition music while the resolution of a monitor (screen) could determine the experience of watching high-definition video content.

Thus, QoS as a concept describing the quality of data transmission is crucial to understanding QoE, but it can only shed light on part of the overall picture. As a result, QoE-driven network management strategies have gained importance in recent years as the optimization of QoE and thus consumer experience is considered a major strategic objective for providers of content and applications who expect to gain a competitive advantage in the marketplace from it (see, for example, Akamai, 2016a; Varela, Skorin-Kapov, & Ebrahimi, 2014).

… and in practice

A recent study for Ofcom 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.
- 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 said this, Jigsaw (2016)

[5] A number of articles provide an overview of the discussion. For a technical overview of Internet quality in the context of network performance, see, for example, Claffy and Clark (2015). For earlier works emphasizing the relation between user experience and technical network performance, see, for example Bouch et al. (2000) or Bouch and Sasse (2001), while for more recent discussion of Internet quality as perceived by users, see Möller and Raake (2014). Standardization bodies like the ITU-T, ETSI and the IETF have also worked on relevant issues (Varela et al., 2014, p. 87).

[6] In their (superseded) recommendation ITU-T E.800 from 1994, the International Telecommunication Union (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 et al. (2014, pp. 87ff.).

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.[7] Bundles, which can include third party application services 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. 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 Fig. 1 (below). Fig. 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 customer services. This category describes factors like maintenance or billing that have an impact on consumer experience in their own right but can be considered independent from actual broadband usage. 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 broadband 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 Fig. 1, each can, in turn, be further sub-divided. Before each is recounted in turn below, it is necessary to remark that different colours or types of dashed lines indicate the degree to which each component can be influenced by a typical broadband Internet access provider, that is, the ISP. This is important as subscribers typically turn to their 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 providing ISP.

5.1. 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. As co-ordinating between these stakeholders in the UK has been found to be fraught with difficulties (Jigsaw, 2016, pp. 5/21f.), Ofcom recently asserted that this needs to be improved (Ofcom, 2016b), and issued a consultation on potential regulations focusing on the quality of Openreach upstream products (Ofcom, 2017). 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.

5.2. User

User preferences and expectations are heterogeneous and shape how content and application services are perceived. Considerable variations between consumers exist and are manifested in different usage patterns, requirements and expectations. In addition to digital literacy, user preferences are shaped by socio-economic, cultural, geographic and demographic characteristics (Reiter et al., 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.[8] Consumption patterns are differing depending on, for example, whether a smartphone or desktop PC with a high resolution monitor is used (Reiter et al., 2014; Sandvine, 2016b, pp. 6ff.).

5.3. 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, home networks might impede consumer experience as components may constitute performance bottlenecks presenting barriers to exploit subscribed-to access speeds. The use of WiFi is especially fraught with difficulties as de facto available data rates may be low. Imagine, for example, a situation where multiple users share a single WiFi router in order to access the Internet. In general, the performance of wireless

[7] For a discussion of bundling within the telecommunication industry see, for example, Mikkonen, Niskanen, Pynnönen, and Hallikas (2015). While traditionally telecommunications contracts for end users did not include content-related components, the example of ESPN3 in the United States serves as an example of the bundled approach. End users subscribing to partnering ISPs get access to ESPN3 content and pay for this with their monthly fee (compare with, for example, Clark, Lehr, & Bauer, 2016, pp. 349f.).

[8] For selected fixed broadband networks in North America, a recent report by Sandvine (2016b) finds that, per typical day, examined households use an average of 7.1 devices to connect to the Internet. 6% of examined households use more than 15 devices per day (Sandvine, 2016b, p. 3). The report also shows heterogeneous usage patterns depending on the device that is used to get Internet access.

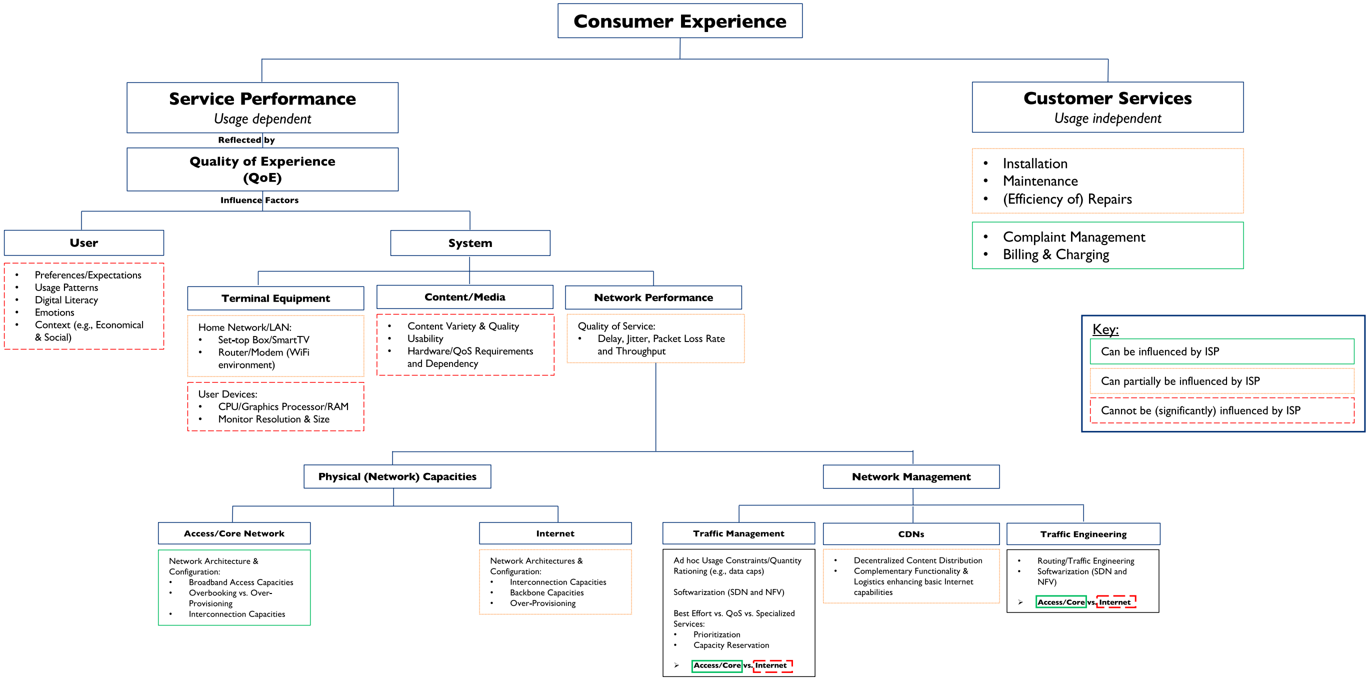

Fig. 1. The many dimensions of consumer experience.
Source: Authors

communications depends on a number of factors such as the distance between the WiFi antenna and the user device and structural conditions like the presence, number and composition of walls between the antenna and user device. Furthermore, congestion in Local Area Networks (LAN) or the simultaneous use of multiple application services may lead to (aggregate) capacity requirements exceeding available data rates. In addition, the misalignment between the capabilities of the home network and the available broadband access speeds need to be taken into account (Ou, 2008, pp. 28f.). This may impair application performance and may thus result in poor consumer experience.

The variety of devices enabling Internet access has further implications on consumer experience. Devices range from 'traditional' desktop personal computers (PCs) 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, tablets and smartphones differ in terms of screen size, CPU speed, quality of their graphics processor and how much memory (RAM) they contain. 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 PC due to the larger screens and arguably easier search functions available online compared to mobile apps.

5.4. Content and media

Consumer experience is naturally limited by the variety and available quality of content and applications. In cases of bundled subscriptions, media portals may not offer a full variety of movies or series. For example, 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). While this may be related to a region specific business strategy or copyright restrictions, ISPs may use content bundling as a competitive strategy to differentiate their access products. This may include exclusive contracts with specific content providers.[9] Furthermore, the available video resolutions may not include high definition (HD) content.[10] Consumer experience is thus negatively affected by these constraints, irrespective of the actual network performance with which corresponding content is delivered. However, adaptive streaming techniques as used by a number of video streaming services like Netflix, dynamically adapt sending rates and thus video resolutions to current network conditions (see, Adhikari et al., 2012). Lower video resolutions typically lead to losses in consumer experience (see, for example, Seufert et al., 2015, p. 480f).

Furthermore, content and applications may be delivered on a device dependent basis that may impact on their usability. Indirectly affecting consumer experience are thus the requirements and responses of different content and application services regarding the devices (that is, CPU, graphics processing, etc.) and specific QoS levels. 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 & Clark, 2015).

5.5. Network performance

In order to achieve satisfactory performance, different application services have heterogeneous requirements regarding QoS. Network performance constitutes a crucial input into meeting these requirements and to render possible a good consumer experience. A number of parameters need to be considered. Focusing on the speed of data transmission, throughput describes 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. End-to-end means that communications between sender and receiver might require data packets to traverse multiple networks operated by different and competing entities. Thus, although high access speeds may be available, performance bottlenecks somewhere in the delivery chain may lead to rather low end-to-end throughput rates and impaired consumer experience. In addition, parameters like delay, jitter and packet loss rates play an important role, especially for interactive real-time applications like VoIP that are rather sensitive to these parameters. Describing network performance, 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 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 segments of the network which are administered and operated by the access providing ISP, and those that can be accessed via the Internet based on interconnections with other networks that are operated by other entities. Fig. 2 provides a stylized illustration. The access network begins upstream of the user-network-interface where data traffic is handed over from the local home network to the access segment of the ISP network. Typically, end-to-end QoS levels are influenced by different factors and market players. ISPs provide consumers with broadband Internet access, that is, Internet connectivity and have a broad influence on end-to-end QoS levels as access capacities determine upper bounds for available

[9] See footnote 7 for the example of ESPN3 and partnering ISPs in the United States.

[10] 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).

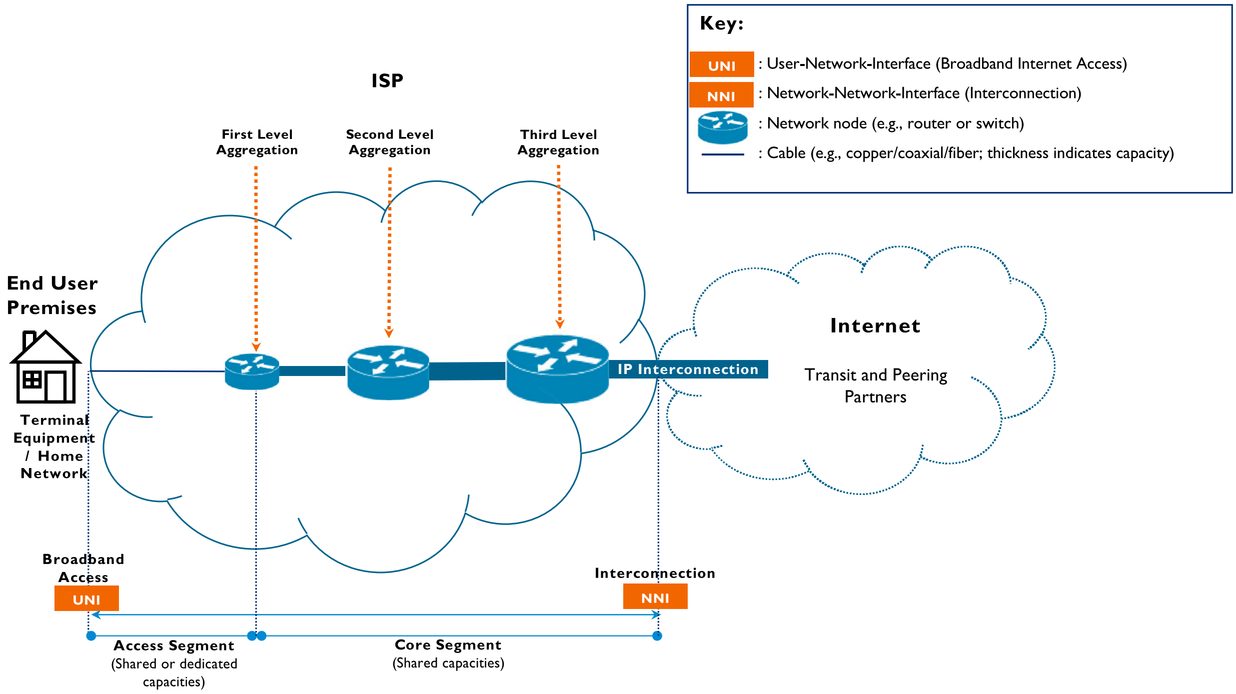

Fig. 2. A stylized illustration of the ISP network: Access versus core.
Source: Authors based on International Telecommunication Union (2011); Arthur D. Little and Liberty Global (2014).

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 and configuration, as exemplified by over-provisioning of network capacities on the one hand and overbooking strategies at multiple aggregation points on the other, may have different effects on the scarcity of specific network resources and thus crucially impact on the available QoS levels.

Equally important is network management. Although many access products are based on flat fees, these might entail ad hoc quantity rationing strategies based on usage constraints such as monthly data caps. 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. Although 'best effort' principles imply that all data packages are treated equally, active traffic management techniques may be used to mitigate the negative effects of network congestion. These traffic management techniques are based on QoS mechanisms that prioritise data packets or reserve bandwidth capacity, and are typically used to provide differentiated service qualities.

In the UK, leading ISPs comply to a 'Voluntary Industry Code of Practice of Traffic Management Transparency for Broadband Services' (Broadband UK, 2013). Accordingly, 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 reach all content and end users connected to the Internet, regardless of where these are located, ISPs enter interconnection agreements. The interconnection ecosystem is complex and different types of settlement-based or settlement-free interconnections with other ISPs, large content providers or providers of Content Delivery Networks (CDNs) may be established.[11] In many cases, end-to-end delivery requires data packets to cross network borders. Hence, origination and termination of data traffic are handled by different entities. In corresponding cases, ISPs inevitably lose control over end-to-end QoS levels. Bargaining on the terms of interconnections (including capacities), but also routing/traffic engineering and network management beyond the borders of the access providers play a crucial role in determining resulting QoS levels. For example, contractual inefficiencies and adverse routing strategies – for example, hot potato routing – may impair end-to-end QoS levels of inter-provider traffic.

Recognizing this fact, ISPs have made a number of efforts to increase QoE by reducing the distance data packets have to travel between source and destination, as well as by introducing sophisticated technologies to manage capacities more efficiently. Beyond

[11] For an overview over Internet interconnection agreements, see, for example, Faratin et al. (2008).

Table 2
Heterogeneous QoS requirements and device dependency.

Application Service	Throughput		Delay	Jitter	Packet Loss Rate	Device Dependency
	Downstream	Upstream				
Browsing the Web (text/media)	++/+++	–	++	–	+++	Yes
Email	–	–	–	–	–	No
Cloud Storage/File Sharing	+++	++/+++	+	–	+++	No
Voice over IP	+	+	+++	+++	+	No
Video Teleconferences	+++	+++	+++	+++	+/++	Yes/No
Video Streaming	+++	–	+	–	+	Yes

Key: – = less important; +++ = very important.
Source: based on Stocker (2015); BEREC (2014); Gonsalves and Bharadwaj (2009); International Telecommunication Union (2001).

a trend to enhance traffic engineering and management capabilities based on the increasing softwarization of ISP networks,[12] a seemingly effective strategy is to enter into direct interconnection agreements with fellow ISPs and CDNs at geographically close interconnection points such as Internet Exchange Points (IXPs). Through the latter, the number of players involved in end-to-end packet delivery is reduced. There are several ways in which ISPs can pursue a wide array of CDN strategies to enhance QoS and QoE levels. Based on their ability to introduce enhanced traffic management capabilities complementary to basic best effort-based packet delivery, CDNs provide means to optimize QoE for some types of content and applications by replicating and caching these on servers in close proximity to consumers (Stocker, Smaragdakis, Lehr, & Bauer, 2017).[13] Recently, a number of ISPs have entered into strategic alliances with CDNs in order to gain more control over QoS levels and to enhance the consumer experience (Frank et al., 2013). ISPs may even deploy CDN servers within their networks. As relevant end-to-end communications between CDN edge servers and end users can be shifted entirely within the boundaries of the ISP network, QoS control can be increased and QoE can be optimized.[14]

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 (see Table 2).

6.1. Cloud storage and file sharing

A trend towards backup solutions and data storage in the cloud is observable. Application services like Dropbox 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. The 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.

6.2. 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 and require rather symmetric up- and downstream data rates. For voice calls, Skype recommends 100 kbps 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 8 Mbps downstream and 512 kbps upstream are

[12] New developments are based on Software Defined Networking (SDN) and Network Function Virtualization (NFV). For an overview over corresponding technologies, see, for example, Naudts, Tavernier, Verbrugge, Colle, and Pickavet (2016) or Metzler (2015).

[13] CDN service provision is based on a decentralized content distribution approach and allows to provide end-to-end QoS levels customized to meet application-specific requirements in a way that consumer experience is optimized. While CDN services are typically used for media delivery (in particular video) and website acceleration, a number of mechanisms (for example, adaptive streaming, prefetching or front end optimization) is used to increase QoE (see, for example, Knieps & Stocker, 2016, p. 322). In 2015, more than 40% of today's global Internet traffic and more than 60% of video traffic are already delivered via CDNs (Cisco, 2016, p. 18). Ofcom (2016e, p. 57) reports that CDNs account for 76% of fixed interconnection traffic. For an overview of CDN service provision see, for example, Stocker et al. (2017).

[14] Analyzing the case of Netflix's server deployment strategy, Böttger, Cuadrado, Tyson, Castro, and Uhlig (2016) find that corresponding practices are widespread among ISPs in the UK. They report that 63 Netflix servers are deployed within BT's, 6 within Plusnet's, 71 within Sky's, 37 within TalkTalk's, and 41 within Virgin's networks.

recommended (Skype, 2016). Google Hangout recommends symmetric data rates of 2.6 Mbps for video calls between two devices. For group calls, asymmetric data rates of 2.6 Mbps upstream and, depending on the number of communicating devices involved, up to 4 Mbps downstream 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).

6.3. 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.[15] Netflix offers a number of different video resolutions. For video streams in 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).

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 300 kbps and 9 Mbps (Google, 2016b). Inherent to video streaming services are asymmetric requirements for data rates. While rather small requests result in low data volumes travelling upstream, 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, 2016c).[16]

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 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 monotonically increasing? That is, do 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. With increasing access speeds, however, the factors noted in Sections 4–6 come to the fore and the relationship changes.

The reason for this lies in the very nature of the value chain – for the relationship to be monotonically increasing, improvements across the whole delivery chain will need to be aligned and increase in unison.[17] 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 – some consumers are willing to pay more for higher access speeds, while others are not. The motivation for the higher willingness to pay may be based on the expectation that higher access speeds provide additional utility. As noted in previous sections, the relationship between higher access 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

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

[16] 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, 2016c, 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, 2016c, p. 18).

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

experience breaks down if access speeds reach a critical threshold that require, for example, other network components and contractual arrangements to adapt. As these adaptions do not occur or eventually become technically impossible, the performance bottleneck shifts to somewhere else in the delivery chain. Consumer experience does not increase but instead begins to decline as customer expectations can no longer be met.

Empirical evidence for performance bottlenecks outside the access network can be found in a number of instances. 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 their home networks, 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). While Ofcom went as far as making an app freely available to check the quality of WiFi connections, the role of WiFi as a performance bottleneck was recently analysed by Sundaresan, Feamster, and Teixeira (2016). They found that the likelihood that WiFi is likely to constitute a performance bottleneck substantially increases as access speeds customers subscribe to exceed 20 Mbps.

Outside the home network, the value chain is complex. It involves a range of infrastructure providers, who may use different technologies and traffic management strategies within 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.[18] Ofcom (2015b) identifies where across the delivery 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 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 source of issues affecting the performance of applications based on the cloud or video conferencing (Ofcom, 2015b, p.55).

Unfortunately, it is unclear from Ofcom (2015b) what role speed plays in someone deciding that their consumer 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 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; Krämer, Wiewiorra, & Weinhardt, 2013; Knieps & Stocker, 2015; 2016). Measures taken by the 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.[19] 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).

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, the interpretation of measurement results, as well as the compilation of individual measurements into a 'big picture' of consumer experience presents a daunting challenge (Claffy et al., 2016). 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 ISP are more readily available than those of a content provider or another ISP.[20]

[18] 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 for the 3rd quarter of 2016 show that average connection speeds are 14.627 Mbps, while average peak connection speeds are given at 62.882 Mbps (Akamai, 2016b). This shows that on average, available speeds are only 23,26% 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 lower average connection speeds.

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

[20] 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).

8. Conclusion

With the increasing complexity of the Internet ecosystem and emerging trends like the IoT, the number of devices connected to the Internet and demand for bandwidth capacities are continuously increasing. The concomitant proliferation of innovative business models and the emergence and increasing adoption of a wide array of heterogeneous application services further contribute to a highly dynamic and rapidly evolving value chain that delivers services to the consumer. In this paper, we demonstrated that consumer experience is made up of a myriad of interacting factors that are entirely, partially, or even not under the control of the access providing ISP. Although 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. Rather, broadband access speed is necessary to provide consumers with a good experience, but it is not sufficient – in fact, there is more to consumer experience than just broadband access speed. Reflecting this, our analysis suggests a more nuanced approach to understanding consumer experiences and lays the foundation for policy recommendations. In addition, implications for future research can be derived.

We have shown that consumer experience is shaped by the ‘weakest link’ in the value chain. Thus, an appreciation of the complexities involved in identifying and assessing the location and impact of performance bottlenecks, which can occur at any point across the whole value chain and may dynamically change their location, is essential to inform and meaningfully assess broadband related policy initiatives. For example, although often overlooked, the role that home networks located in the end user premise play, in terms of both the role of WiFi connecting the router to the device as well as how the physical characteristics of a building impact on the signal propagation, has been identified to be a major source of problems. This suggests one area for policy initiatives to be undertaken in, namely, educating consumers as to where to site their router, how to use their devices, and how to optimize the use of WiFi channels.

Our analysis, which demonstrates an inverted U-shaped relationship between broadband speeds and consumer experience, offers further implications for the current debate in the UK regarding universal service (Ofcom, 2016f) and which can also be extended to a broader set of issues regarding broadband related industrial policy. While providing everyone who desires it with a 10 Mbps connection will undoubtedly bring about benefits, especially to those who lack a connection or whose current speeds are below this threshold, it is not necessarily the case that these benefits increase in line with faster broadband speeds. Focusing solely on broadband speed is overly simplistic and overlooks the influence that the value chain has on shaping consumer experiences. While isolated and local strategies aimed at increasing broadband access speeds may in some way enhance consumer experience, their effectiveness may be limited as they could result in shifts of performance bottlenecks to other parts of the value chain. A 10 Mbps universal service obligation may probably not be sufficient to bring about the sort of experiences consumers desire, especially when anticipating the evolutionary path of the Internet and relevant applications. This offers an argument for increasing the minimum speeds. In the UK, speed targets of 30 Mbps have recently been debated by the House of Lords (Hansard, 2017).

While industry policy and universal service regulations may play an important role in fostering the deployment of faster broadband, improvements in speed are possible through a variety of broadband technologies with heterogeneous capabilities. For example, G.fast or next generation cable access (for example based on DOCSIS 3.1) significantly improve speeds available from using copper or cable-modem based broadband access technologies while full-fibre deployments enable further increases in access speeds to multiple Gbps (Middleton, 2016; Ofcom, 2016e, pp. 23f.). Although BT has begun G.fast trials in the UK and promised to expand the use of fibre in its network (Whalley & Curwen, 2017), these technologies raise additional broader questions, for example, how fast should or can they be incorporated into the network by operators and then adopted by consumers? Not only does this raise the thorny issue of the relationship between infrastructure investment and operator strategy, but also how governments can encourage investment on the one hand and consumer adoption on the other. Further research is required in both of these areas.

Beyond the aforementioned policy implications, our paper has implications for future research. We described the link between network performance, QoS and QoE and demonstrated their importance for consumer experience. While the use of QoE has been advantageous so far, further research is needed to enhance the understanding of QoE 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 relevant 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.

Acknowledgements

Previous versions of this paper were presented at the 27th European regional conference of the International Telecommunications Society, 7th to 9th September 2016, Cambridge, UK and to seminars held at the Department of Quantitative Economics, University of Complutense de Madrid, 25th April 2017, Madrid, Spain; and, Telecom École de Management, 18th May 2017, Évry, France. We are grateful for the feedback received from these presentations, as well as to those made by the reviewers. All errors remain the responsibility of the authors.

References

Adams, A. (2015). *Ambitious target set for rural broadband*, 6 October. available at: https://www.beehive.govt.nz/release/ambitious-target-set-rural-broadband.
Adhikari, V. K., Guo, Y., Hao, F., Varvello, M., Hilt, V., Steiner, M., & Zhang, Z. (2012). Unreeling Netflix: Understanding and improving multi-CDN movie delivery. In *Proceedings of IEEE INFOCOM* (pp. 1620–1628).

Akamai (2016a). *Network experience Analytics*. available at: https://www.akamai.com/de/de/solutions/products/network-operator/network-experience-analytics.jsp#123.

Akamai (2016b). *Connectivity Visualizations*. available at: https://www.akamai.com/uk/en/our-thinking/state-of-the-internet-report/state-of-the-internet-connectivity-visualization.jsp.

Amazon (2016). *Amazon video system requirements for computers*. available at: www.amazon.com.

Apple (2016). *iPhone 6*. available at: http://www.apple.com.

Arthur D. Little, & Liberty Global. (2014). *The future of the Internet: Innovation and investment in IP interconnection*. May. available at: www.adlittle.com.

Bauer, S., & Lehr, W. H. (2015). Gigabit broadband, interconnection, and the challenge of managing expectations. In *Paper presented at the 43rd research conference on communication, information and internet policy (TPRC), 25–27 September*. available at: ssrn.com.

BBC (2016). *Connected TV - what internet speed do I need for playing programmes?*. available at: iplayerhelp.external.bbc.co.uk.

Body of European Regulators for Electronic Communications (BEREC) (2010). *BEREC Response to the European Commission's consultation on the open Internet and net neutrality in Europe*. BoR (10) 42. available at: www.berec.europa.eu.

Body of European Regulators for Electronic Communications (BEREC) (2014). *Monitoring quality of Internet access services in the context of net neutrality*. BoR (14) 117. available at: www.berec.europa.eu.

Böttger, T., Cuadrado, F., Tyson, G., Castro, I., & Uhlig, S. (2016). *Open connect everywhere: A glimpse at the internet ecosystem through the lense of the Netflix CDN*, 17 June. available at: https://arxiv.org/abs/1606.05519.

Bouch, A., Kuchinsky, A., & Bhatti, N. (2000). Quality is in the eye of the beholder: Meeting users' requirements for Internet quality of service. In *Proceedings of the SIGCHI conference on human factors in computing systems (CHI'00)* (pp. 297–304).

Bouch, A., & Sasse, M. A. (2001). Why value is everything: A user-centered approach to internet quality of service and pricing. In L. Wolf, D. Hutchison, & R. Steinmetz (Eds.), *Quality of service – IWQoS 2001, LNCS 2092* (pp. 59–72). Berlin, Germany: Springer.

Broadband Commission for Sustainable Development (2016). *The State of Broadband: Broadband catalyzing sustainable development*. September 2016.

Broadband UK (2013). *Voluntary industry code of practice on traffic management transparency for broadband services*. updated March 2013. available at: http://www.broadbanduk.org/wp-content/uploads/2013/08/Voluntary-industry-code-of-practice-on-traffic-management-transparency-on-broadband-services-updated-version-May-2013.pdf.

Cisco (2016). *Cisco visual networking index: Forecast and methodology, 2015-2020*. June 1. available at: www.cisco.com.

Claffy, kc, & Clark, D. D. (2015). Adding enhanced services to the Internet: Lessons from History. In *Paper presented at the 43rd research conference on communication, information and internet policy (TPRC), 25–27 September, Arlington, VA*. available at: ssrn.com.

Claffy, kc, Clark, D. D., Bauer, S., & Dhamdhere, A. (2016). Policy challenges in mapping internet interdomain congestion. In *Paper presented at the 44th research conference on communication, information and internet policy (TPRC), 29 September - 1 October, Arlington, VA*. available at: ssrn.com.

Clark, D. D. (2016). *Keynote: Internet measurement, presentation at NANOG 66*, 8-10 February, San Diego, CA. available at: https://www.youtube.com/watch?v=2GE8qShOoJ4.

Clark, D. D., Lehr, W. H., & Bauer, S. (2016). Interconnection in the internet: Peering, interoperability and content delivery. In J. M. Bauer, & M. Latzer (Eds.), *Handbook on the economics of the internet* (pp. 344–362). Cheltenham, UK: Edward Elgar.

Department for Culture, Media & Sport (2015). *Government plans to make sure no-one is left behind on broadband access*, 7 November. available at: www.gov.uk.

Department for Culture, Media & Sport (2016). *A new broadband universal service obligation – consultation*, 23 March. available at: www.gov.uk/dcms.

Economist Intelligence Unit (2012a). *Full speed ahead: The government report Q1 2012*. March. London, UK: Economist Intelligence Unit.

Economist Intelligence Unit (2012b). *Superfast Britain? Myths and realities about the UK's broadband future*. London, UK: Economist Intelligence Unit.

Ericsson, Arthur D. Little and Chalmers University of Technology. (2013). *Socio-economic effects of broadband speed, September*. available at: www.ericsson.se.

European Commission (2016). *Connectivity for a competitive digital single market - towards a european gigabit society, communication from the commission to the european parliament, the Council, the european economic and social committee and the committee of the regions*. COM 2016(587) final, 14 September.

European Parliament and Council (2015). *Regulation (EU) 2015/2120 of the European Parliament and of the Council of 25 November 2015 laying down measures concerning open internet access and amending directive 2002/22/EC on universal service and users' rights relating to electronic communications networks and services and Regulation (EU) No 531/2012 on roaming on public mobile communications networks within the Union, 26.11.2015, OJ, L 310/1-18, Brussels*.

Ezell, S., Atkinson, R., Castro, D., & Ou, G. (2009). *The need for speed: The importance of next-generation broadband networks*. The Information Technology & Innovation Foundation. available at: www.itif.org.

Faratin, P., Clark, D., Bauer, S., Lehr, W., Gilmore, P., & Berger, A. (2008). The growing complexity of internet interconnection. *Communications & Strategies, 72*(4), 51–71.

Feasey, R. (2016). *Superfast universal service in the UK*, 18 January. available at: www.fronfraithltd.com.

Finder.com. (2016). *Netflix USA vs. the world: Content libraries compared'*. available at: www.finder.com.

Firoiu, V., Le Boudec, J.-Y., Towsley, D., & Zhang, Z.-L.- (2002). Theories and models for Internet quality of service. *Proceedings of the IEEE, 90*(9), 1565–1591.

Frank, B., Poese, I., Lin, Y., Smaragdakis, G., Feldmann, A., Maggs, B., et al. (2013). Pushing CDN-ISP Collaboration to the limit. *ACM SIGCOMM Computer Communication Review, 43*(3), 34–44.

Gijón, G., Whalley, J., & Anderson, G. (2016). Exploring the differences in broadband access speeds across Glasgow. *Telematics and Informatics, 33*(4), 1167–1178.

Gonsalves, T. A., & Bharadwaj, A. (2009). *Comparison of AT-Tester with other popular testers for quality of service experience (QoSE) of an Internet connection*. August. available at: lantana.tenet.res.in.

Google (2016a). *Hangouts system requirements on your computer*. available at: support.google.com.

Google (2016b). *Live encoder settings, bitrates and resolutions*. available at: support.google.com.

Google (2016c). *Video quality report*. available at: https://www.google.com/get/videoqualityreport/.

Government of Australia. (2016). *NBN Co Ltd statement of expectations*, 24 August.

Hansard (2017). *Digital economy bill 22 February* (Vol. 779). available at: www.parliament.co.uk.

International Telecommunication Union (1994). *Terms and definitions related to quality of service and network performance including dependability, ITU-T Recommendation E.800, 08/1994*. available at: www.itu.int.

International Telecommunication Union (2001). *End-user multimedia QoS categories, ITU-T recommendation G.1010, 11/2001*. available at: www.itu.int.

International Telecommunication Union (2011). *Network performance objectives for IP-based services, ITU-T Recommendation Y.1541, 12/2011*. available at: www.itu.int.

Jigsaw (2016). *Quality of service in telecoms: Residential consumers and SME experience of quality of service in fixed line, broadband and mobile telecoms*. February. London, UK: Jigsaw Research.

Kantar Media (2013). *Transparency in internet traffic management, prepared for Ofcom*. September. available at: www.ofcom.org.uk.

Knieps, G., & Stocker, V. (2015). Network neutrality regulation: The fallacies of regulatory market splits. *Intereconomics, 50*, 46–51.

Knieps, G., & Stocker, V. (2016). Price and QoS differentiation in all-IP networks. *International Journal of Management and Network Economics, 3*(4), 317–335.

Koutroumpis, P. (2009). The economic impact of broadband on growth: A simultaneous approach. *Telecommunications Policy, 33*(9), 471–485.

Krämer, J., Wiewiorra, L., & Weinhardt, D. (2013). Net neutrality: A progress report. *Telecommunications Policy, 37*(9), 794–813.

Mack, E. A. (2014). Business and the need for speed: The impact of broadband speed on business presence. *Telematics & Informatics, 31*(4), 617–627.

Metzler, J. (2015). *The 2015 guide to SDN and NFV*. January. available at: https://www.a10networks.com/sites/default/files/resource-files/2015Ebook-A10-all.pdf.

Middleton, C. (2016). Moral fibre. *InterMEDIA, 44*(1), 31–34.

Mikkonen, K., Niskanen, H., Pynnönen, M., & Hallikas, J. (2015). The presence of emotional factors: An empirical exploration of bundle purchasing process. *Telecommunications Policy, 39*(8), 642–657.

Ministry of Business, Innovation & Employment. (2017). *The ultra-fast broadband initiative and getting connected*. available at: http://www.mbie.govt.nz/info-services/sectors-industries/technology-communications/fast-broadband/the-ufb-initiative-and-getting-connected.

Möller, S., & Raake, A. (2014). *Quality of experience – Advanced concepts, applications and methods*. Heidelberg, Germany: Springer.

Mölleryd, B. G. (2015). *Development of high-speed networks and the role of municipal networks, OECD Science*. Technology and Industry Policy Papers, No. 26. available at: http://dx.doi.org/10.1787/5jrqdl7rvns3-en.
Naudts, B., Tavernier, W., Verbrugge, S., Colle, D., & Pickavet, M. (2016). Deploying SDN and NFV at the speed of Innovation: Toward a new Bond between standards development organizations, industry fora, and open-source software projects. *IEEE Communications Magazine, 54*(3), 46–53.
Netflix (2016). *Internet connection speed recommendations*. available at: help.netflix.com.
OECD (2011). *National broadband plans, OECD Digital Economic papers*. No. 181. available at: www.oecd.org.
Ofcom (2013). *A guide to internet traffic management*. September. available at: www.ofcom.org.uk.
Ofcom (2015a). *Communications market report*, 6 August, London, UK: Ofcom.
Ofcom (2015b). *Connected nations*, 1 December, London, UK: Ofcom.
Ofcom (2016a). *The consumer experience*. February, London, UK: Ofcom.
Ofcom (2016b). *Making digital communications work for everyone*, 25 February. available at: www.ofcom.org.uk.
Ofcom (2016c). *Telecom & pay TV complaints Q1 (January to march) 2016*, 8 July, London, UK: Ofcom.
Ofcom (2016d). *Communications market report*, 4 August, London, UK: Ofcom.
Ofcom (2016e). *Connected nations*, 16 December, London, UK: Ofcom.
Ofcom (2016f). *Achieving decent broadband connectivity for everyone - technical advice to UK Government on broadband universal service*, 16 December, London, UK: Ofcom.
Ofcom (2017). *Quality of service for WLR, MPF and GEA: Consultation on proposed quality of services Remedies*, 31 March, London, UK: Ofcom.
Ookla (2016). *Speedtest market report: United Kingdom*, 15 November. available at: www.speedtest.net.
Ou, G. (2008). *Managing broadband networks: A Policymaker's guide*. The Information Technology and Innovation Foundation. December.
Qiang, C. Z.-W., Rossotto, C. M., & Kimura, K. (2009). *Economic impacts of broadband, in, world bank, information and communications for development 2009*. Washington DC, USA: The World Bank.
Raake, A., & Egger, S. (2014). Quality and quality of experience. In S. Möller, & A. Raake (Eds.), *Quality of experience – Advanced concepts, applications and methods* (pp. 11–33). Heidelberg, Germany: Springer.
Rathbone, D. (2016). *Superfast broadband coverage in the UK*, 4 July, Briefing paper number CBP06643. House of Commons Library. available at: www.parliament.uk/commons-library.
Read, V. (2016). *Time for a broadband shake-up?* Governup. available at: www.governup.org.
Reiter, U., Brunnström, K., de Moor, K., Larabi, M.-C., Pereira, M., Pinheiro, A., et al. (2014). Factors influencing quality of experience. In S. Möller, & A. Raake (Eds.), *Quality of experience – Advanced concepts, applications and methods* (pp. 55–72). Heidelberg, Germany: Springer.
Riddlesden, D., & Singleton, A. D. (2014). Broadband speed equity: A new digital divide? *Applied Geography, 52*, 25–33.
Rohman, I. K., & Bohlin, E. (2014). *Does broadband speed really matter for driving economic growth?*. Investigating OECD countries. available at: ssrn.com.
Sandvine (2016a). *Global internet phenomena report: Latin America & North America*. June. available at: www.sandvine.com.
Sandvine (2016b). *Global internet phenomena report - spotlight: Inside the connected home, Latin America & North America*. August. available at: www.sandvine.com.
Seufert, M., Egger, S., Slanina, M., Zinner, T., Hoßfeld, T., & Tran-Gia, P. (2015). A survey on quality of experience of HTTP adaptive streaming. *IEEE Communication Surveys & Tutorials, 17*(1), 469–492.
Shepardson, D. (2016). *FCC not to investigate Netflix throttling of some mobile consumers*. Reuters, 31 March. available at: www.reuters.com.
Singer, H., Caves, K., & Koyfman, A. (2015). *The empirical link between fibre-to-the-premises deployment and employment: A case study in Canada*. Washington DC, USA: Economists Incorporated.
Skype (2016). *How much bandwidth does Skype need?*. available at: support.skype.com.
Stocker, V. (2015). Interconnection and capacity allocation for All-IP Networks: Walled gardens or full integration?. In *Paper presented at the 43rd research conference on communication, information and internet policy (TPRC), 25–27 September*. available at: ssrn.com.
Stocker, V., Smaragdakis, G., Lehr, W. H., & Bauer, S. (2017). *The growing complexity of content delivery networks: Challenges and implications for the Internet ecosystem*. Telecommunications Policy, forthcoming.
Struble, T. W. (2016). On the relationship between QoS & QoE: Why differential traffic management on the internet is not a Zero-Sum practice. In *Paper presented at the 44th research conference on communication, information and internet policy (TPRC), 29 September - 1 October, Arlington, VA*. available at: ssrn.com.
Sundaresan, S., Feamster, N., & Teixeira, R. (2016). Home network or access Link? Locating last-mile downstream throughput bottlenecks. In T. Karagiannis, & X. Dimitropoulos (Eds.), *Passive and Active Measurement: 17th International Conference PAM 2016-Proceedings, Cham et al* (pp. 111–123). Springer.
Varela, M., Skorin-Kapov, L., & Ebrahimi, T. (2014). Quality of service versus quality of experience. In S. Möller, & A. Raake (Eds.), *Quality of experience – Advanced concepts, applications and methods* (pp. 85–96). Heidelberg, Germany: Springer.
Whalley, J., & Curwen, P. (2017). From phones to football: The changing strategic focus of BT. *Telematics & Informatics, 34*(5), 798–809.
WIK, Deloitte, & IDATE. (2016). *Regulatory, in particular access, Regimes for network investment models in Europe*. A study prepared for the European Commission DG Communications Networks, Content & Technology, Final report, September.
Wu, T. (2003). Network neutrality, broadband discrimination. *Journal on Telecommunication and High Technology Law, 2*, 141–179.
Yiu, C., & Fink, S. (2012). *The superfast and the furious – priorities for the future of UK broadband policy*. Policy Exchange. available at: www.policyexchange.org.uk.