Economic Impact of Technology Standards

Annexes to the Report

The past and the road ahead

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COMPASS LEXECON

Authors: Jorge Padilla, John Davies and Aleksandra Boutin

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Contents

Case Study: Mobile Telephony

Introduction

A.1 Mobile telephony is an industry very heavily dependent on technological standards. The evolution of standards in this industry has shaped the technological and commercial development of the industry. Governments played the leading role in the early 1G and 2G eras, especially in Europe, leading to regional standards that effectively supported (and were sponsored by) firms acting as national champions. However, as the industry has further developed, standards have become based much more upon open participation in industry bodies. This has led to more open competition in sales of devices and also to wider participation in R&D.

A.2 The effects on technological progress have been impressive: vastly more capable devices sold at declining prices. At least as impressive as this measure, however, has been the flexibility of the mobile telephony technologies to accepting new technologies and new uses for the devices. It is not merely that 4G phones perform the functions of 2G phones more capably: they play entirely different roles in our lives. The openness of the technology platforms underlying mobile telephony to change and to add-ons derives in part from the way standards are set in this industry.

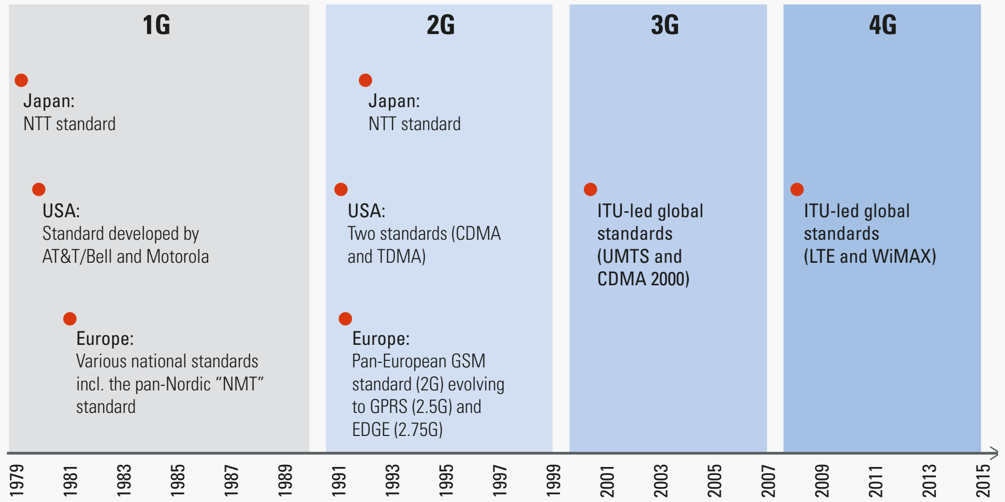
A.3 In this annex we therefore provide a more detailed account of the history of technological, commercial and institutional developments in the mobile telephony industry, with a particular focus on the central role of standard development in this story.

Historical overview

A.4 Telephones were first introduced in 1876 but the first mobile call was made in 1973, followed by the development of the 1G system of mobile telephony standards by the 1980s. In the late 1980s, the second generation (2G) of mobile technology was developed which improved the quality of the calls and made better use of the radio spectrum. However, there was no common 2G standard across the US, Europe and Japan.

A.5 The development of the third generation (3G) started in the 1980s under the leadership of the International Telecommunication Union, a UN organisation, which had national telecoms authorities and regulators as well as network operators and device manufacturers as its members. 3G technology standards published by the ITU provided global compatibility, high data rates and opened the way for many new mobile services.

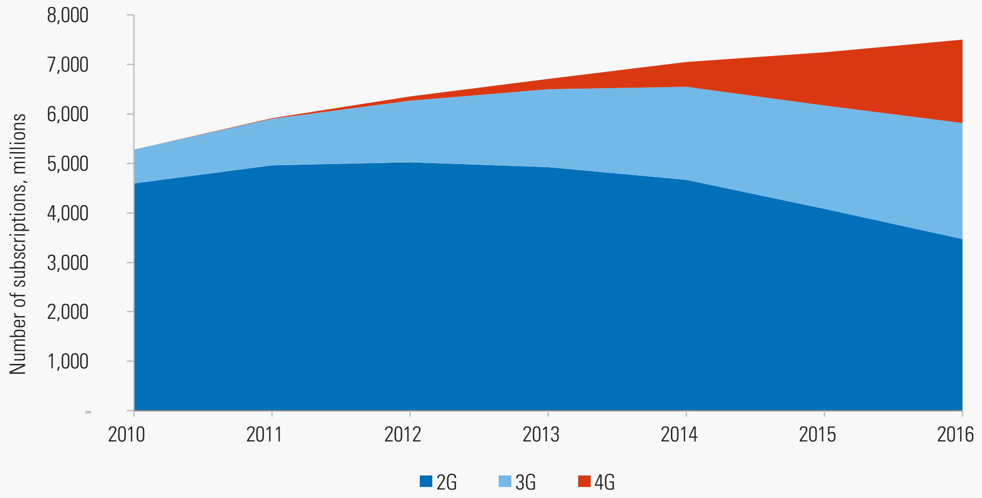
Figure 1: Four generations of cellular standards



Notes: The bars indicate the beginning of commercial deployment of the corresponding standard. Multiple generations of the standards continue to be in operation in parallel (see Figure 34). Analogue systems were discontinued in the US in 2008. NMT and other 1G systems were discontinued in many countries since 2000 but there may be a few remote areas in Russia where 1G standards are still being used.

Source: Various sources (see following sections for further detail).

Figure 2: Global mobile subscriptions, by standard (2010-2016)



Notes: Figures for 2016 are based on forecasts. 2G includes GSM/EDGE, TD-SCDMA and CDMA standards; 3G includes WCDMA/HSPA standards; and 4G includes LTE standard only. These acronyms are discussed in the later sections.

Source: Ericsson (November, 2016) <https://www.ericsson.com/TET/trafficView/loadBasicEditor.ericsson>

A.6 The fourth generation (4G) technologies were also standardised by the ITU, and provided higher data rates for mobile communication, enabling applications including mobile web access and high-definition TV. 4G technologies accepted in the ITU standard were also globally compatible.

A.7 Figure 1 (Page 1) shows the evolution of the various standards over time from 1979 to 2016; and Figure 2 shows the number of subscriptions, by standard, from 2010 to 2016. In 2016, 2G, 3G and 4G systems were being used worldwide with 2G dominating the market with 46.4% of the market. In contrast, 3G had 31.1% of the market and 4G had 22.5% of the market.[1]

This case study begins with an overview of 1G systems followed by a detailed discussion of 2G systems with a focus on the different approaches to standard setting in Europe, USA and Japan. We then discuss the evolution of mobile telephony systems from 2G to 3G and from 3G to 4G, focussing on the ITU-led global standard setting process. Finally, we discuss the evolution of the mobile telephony 'ecosystem' - the technology developers, device manufacturers, network operators and consumers - and its impact on the economy.

First generation mobile telephone systems

A.8 The first generation (1G) of mobile telephone systems were 'analogue' communication standards that were introduced first in 1979. In 1G systems, voice calls were transmitted to radio towers using analogue signals and then transmitted between radio towers and the rest of the telephone system using digital signals.

A.9 1G allowed 'duplex' conversations, i.e. both sides could talk and listen at the same time. In contrast, radio conversations were 'half-duplex' in the sense that parties could either talk (transmit voice) or listen but not both.

A.10 In the late-1970s and the 1980s, the telecoms industry was dominated by monopolies in the US, Japan and in Europe. National governments often had significant influence on standards development. Standards were mandated by the government in all regions except in Nordic countries where the governments played an 'accommodating' role by agreeing to cooperate in the development of a pan-Nordic system and left the standardisation to the public telephone operators and manufacturers such as Ericsson and Nokia (van de Kaa and Greeven 2016).

A.11 The first automated cellular network was launched on a commercial basis in Japan by Nippon Telegraph and Telephone (NTT) in 1979. The government had major influence on NTT and therefore mandated the development of the NTT standard (van de Kaa and Greeven 2016).

A.12 In the US, the 1G standard, called Analogue Mobile Phone System (AMPS), was developed by AT&T/Bell and Motorola and deployed in Chicago in 1979. AMPS was set as the uniform standard for digital communications for the US by the Federal Communications Commission (FCC) in the 1980s (van de Kaa and Greeven 2016; Gandal et al. 2003).

A.13 In Europe, in the early 1980s, countries developed their own standards, so there were nine competing standards in Europe. However, the Nordic mobile telephone operators[2] cooperated to develop a pan-Nordic system called Nordic Mobile Telephony (NMT) standard, which was introduced in 1981 (Bach 2000).

1 Various generations of mobile telecoms co-exist because network technologies often face backwards compatibility issues, which are exacerbated by the underlying legacy infrastructure.

2 Operators in Denmark, Finland, Norway and Sweden.

A.14 The decision in 1982 by the US to adopt the AMPS standard caused many other countries to choose AMPS or a similar technology over NMT (for example, Canada, South Korea, the UK[3] and Hong Kong). North America and the UK subsequently experienced falling service charges through competition between carriers, at about the same time as their fixed line sectors also opened to competition. Handset prices fell as the number of subscribers increased. Although the penetration rates did not rise as fast as in the Nordic countries, the large populations of the US and the UK caused the number of total AMPS and TACS subscribers to pass the total number of NMT subscribers in 1986.

A.15 The Japanese, German, French, and Italian governments took very different approaches to mobile communication, showing more concern for the future competitiveness of their manufacturers. However, the resulting closed standards and the lack of competition contributed towards the eventual opposite result: handset prices and service charges did not fall as fast and thus there was little growth in subscribers (Funk and Methe 2001).

2G mobile telephone systems

A.16 The second generation, or 2G, used digital instead of analogue transmission, allowing a much higher quality of voice communication. The first 2G cellular telecom network was commercially launched in Finland in 1991 (GSM Arena 2011). 2G made much better use of the available spectrum which meant that networks had a higher user capacity (van de Kaa and Greeven 2016). 2G also introduced text messaging services (Short Messaging Service, or SMS) for mobile.

A.17 Additional features such as Multimedia Messaging Services (MMS) and Wireless Application Protocol (WAP) were introduced with two revisions – 2.5G and 2.75G. Internet connectivity using 2G was barely fast enough for casual users and inadequate for business usage (BCG 2015). By 2016, 2G was still the dominant system, with 46.4% of the global market (see Figure 2).

2G standard setting process

A.18 The making of 2G standards was dominated by three models:

a. European model, promoting a single **pan-European standard**;

b. liberalized environment in the U.S. favouring **competing standards**; and

c. national-sponsored Japanese model for a **single national standard** (Gandal et al 2003).

A.19 In USA and Canada the process of determining standards was market-driven, whereas the European Community relied on mandated standards set by the European Telecommunications Standards Institute (ETSI). We discuss the standard setting experiences in the different regions below.

Standard setting in Europe

The origins of a common standard for Europe[4]

A.20 In the early 1980s, European countries had nine competing analogue standards which were not compatible with each other. Europe-wide roaming was not possible. At that time, national operators believed that localized solutions to the development of mobile communications did not make long-term economic sense. Given the daunting R&D costs facing operators and manufacturers, it was essential to be able to exploit the economies of scale inherent in global market penetration. Device manufacturers manufacturing solely for their national markets did not consider sustained investment programmes justifiable.

A.21 In the first half of the 1980s, there were bilateral efforts to agree standards between the national governments of France and the UK and France and Germany but national interests to protect local device manufacturers prevented the success of these negotiations. In contrast, Denmark, Sweden, Norway, Finland and Iceland had successfully cooperated to introduce a common 'NMT' standard for 1G. This standard was later adopted by Saudi Arabia, Thailand, Algeria, Spain, the Netherlands, Belgium and Switzerland.

A.22 The use of the NMT standard in international markets had brought Nordic equipment manufacturers success. Nokia and Ericsson controlled roughly one-fifth of the world market for mobile phones in 1985, while all other European manufacturers together held less than 10%. While concern about domestic industries had impeded bilateral and multilateral cooperation on analogue standards among France, Germany and the U.K., successful cooperation in the Nordic countries strengthened their manufacturers vis-à-vis their international competitors.

Groupe Spéciale Mobile

A.23 To explore the feasibility of collaboration, the French and German national telecoms authorities raised the question at the CEPT (European Conference of Postal and Telecommunications Administrations) in 1982. The CEPT included the national telecoms administrations (government telecoms departments) of 26 countries.[5] Specifically, the group was mainly composed of technocrats and research engineers. Device manufacturers were not a part of the official deliberations but were represented by their respective national governments.

A.24 In 1982, the CEPT established the 'Groupe Spéciale Mobile' (GSM) to develop a standardised system to promote spectrum efficiency, allow international roaming, reduce costs, and improve quality and services (Gozalvez Sempere 2001). Decisions in the GSM were to be made through unanimous agreement of its members. The key players were the national

3 Since AMPS was not perfectly compatible with the frequencies allocated to mobile communication in the UK, carriers adopted a version of AMPS that was modified for the UK market, i.e. TACS.

4 The discussion in this section and the next draws extensively upon Bach (2000).

5 CEPT website: <http://cept.org/cept/>.

Box A.1: ETSI standard setting process

- ETSI abolished the unanimity principle which had led to an impasse in the GSM negotiations. Standards are adopted if they receive 71% of the vote (Van de Kaa and Greeven (2016). Each country has a single vote and voting decisions are decided upon by the respective national standards organisations (NSOs) ETSI forwards the draft standard to the NSOs who then carry out a consultation and decide on the national position for the vote on the standard.[6]
- There are also special interest groups representing operator groups by geographical location or technology. At each plenary session, the chairpersons of various working groups bring members up to date with latest developments.
- These working groups examine issues such as international roaming, harmonization of tariff principles, global marketing, accounting and billing procedures, legal and regulatory matters, time scales for the procurements and deployment of systems, etc.[7]
- Proposals are voted upon, with the number of votes allocated to a member dependent on factors like 'number of subscribers' or GDP.[8]

governments in France, Germany, UK, Italy, and the Nordic countries. GSM, following technical deliberations, decided to pursue a digital standard which would:

a. enable a more efficient management of scarce frequency bands;

b. provide high speech quality;

c. include features such as speech security and data communications;

d. allow smaller and cheaper devices.

Disagreement on standards

A.25 During the deliberations, there were eight proposals for standards submitted by European industry consortia in 1986. However, the requirement for unanimous agreement for accepting proposals led to a deadlock among the members who wanted their proposal to be accepted as the standard.

Intervention by the European Commission

A.26 The European Commission had no formal representation in the CEPT or the GSM, but when the deadlock emerged, the Commission, through its Presentation and Green Paper in 1987, emphasised the need to develop a common telecoms market in Europe. This pressure led to a compromise solution of a standard consisting of different technical components – a basket of modules designed by several industry consortia. In other words, the standard was defined as a set of system functions and not device specifications (Bach 2000).

A.27 The members agreed on the specifications for 2G standards in 1987 that drew on several of the eight component proposals submitted by European industry consortia in 1986. By including variants from different proposals as a part of the "basket standard" solution, the technical specifications ended up being more complex than necessary (Bach 2000). For example, the specifications included two variants of 2G specifications, one variant which was supported by Ericsson and another supported by Nokia, Alcatel, Siemens and Nortel (Meyer 2012).

A.28 The standard developed by the 'Groupe Spéciale Mobile' was called the Global System for Mobile communications (GSM) thereby retaining the same three-letter abbreviation. In September 1987, mobile network operators across Europe signed a Memorandum of Understanding (MoU) to introduce GSM networks by 1991.

European Telecommunications Standards Institute

A.29 ETSI, a consortium of national administrations, operators, and manufacturers, was established in 1988 by the CEPT to develop European standards[9], and took over the development of the GSM (Global System for Mobile communications) standard from the GSM (Groupe Spéciale Mobile) organisation.

A.30 ETSI continues to operate as the official European Standards Organisation, recognized by the European Union, dealing with telecoms, broadcasting and other electronic communications networks and services.[10] ETSI is also a member of an alliance that supports the International Telecommunications Union (ITU) in developing new generations of global wireless standards (see Section A.65).

A.31 ETSI is independent of the EU. Any organisation demonstrating an interest in promoting European telecoms standards has the right to represent that interest in ETSI and to directly influence the standard setting process.[11] Its members comprise government telecoms departments, national standards organisations, regulatory bodies network operators, equipment manufacturers, private service providers, research bodies and users.[12]

6 ETSI website: <http://www.etsi.org/standards/how-does-etsi-make-standards/approval-processes>.
7 ITU website: <https://www.itu.int/osg/spu/ni/3G/casestudies/GSM-FINAL.doc>.
8 GSM website: <http://www.gsmhistory.com/rare-gsm-documents/#political>.
9 ETSI website: <http://www.etsi.org/about/what-we-do>.
10 ETSI website: < http://www.etsi.org/about/what-we-are>.
11 ETSI website: <http://www.etsi.org/about/who-we-are>.
12 ETSI website: <http://www.etsi.org/membership/current-members>.

The consequences of the lack of IPR policies

A.32 In 1988, the main European operators issued an invitation to equipment suppliers to tender for network equipment. These operators, acting together in the GSM MoU, produced a draft procurement procedure in which manufacturers were essentially forced to give up all their IPRs and to provide for free world-wide licenses for essential patents. This arrangement was found to be unacceptable by many manufacturers and resulted in a dispute that threatened the entire GSM program, especially for Motorola from the U.S.

A.33 Under pressure from the manufacturers, the operators decided to drop the condition on IPRs. However, several operators required the manufacturers to sign a declaration in which they agreed to licence the whole GSM community, both suppliers and operators, on fair, reasonable and non-discriminatory conditions. Motorola chose not to accept this declaration, and refused to grant non-discriminatory licences for its patent portfolio that was essential for GSM. Motorola was only prepared to enter into a limited number of cross-licences with selected parties, and also limited the geographic scope of such licences to Europe.

A.34 Several companies, including Matra from France and Dancall from Denmark, made unsuccessful attempts to secure licenses. Of the many Japanese companies that showed very promising prototypes of GSM terminals around 1992, almost none succeeded in getting all the necessary licenses within the first few years of commercial success of the GSM standard. Virtually all equipment was supplied by the companies that took part in the cross-licensing scheme: Ericsson, Nokia, Siemens, Alcatel, and Motorola (Bekkers et al. 2002).

Standard setting in the United States

A.35 The United States developed competing 2G standards through a different process. The US standardisation development was characterised by a shift from the government mandating a standard in 1G to a market-driven strategy for 2G systems.

A.36 In the early 1970s, AT&T had developed the 1G system called AMPS (American Mobile Phone Systems). The first developmental system trial was conducted by Illinois Bell in Chicago in 1978. In 1982, AT&T's monopoly both in telecom services and in standards setting was dismantled by divestiture following US District Court judgement in the United States v AT&T antitrust suit (Tan 2001). Subsequently, the Chicago cellular system began the first AMPS commercial operation by AT&T in 1983.

A.37 The Federal Communications Commission (FCC) did not mandate a specific standard in the US and carriers were free to choose whatever standard they wished. This resulted in the presence of multiple standards (Gandal et al. 2003). Filling the FCC regulatory vacuum, the major telecom companies formed a voluntary consortium, the Cellular Telecommunications Industry Association (CTIA). From 1985, CTIA launched a systematic evaluation of various technological alternatives. This was endorsed by cellular operators and major equipment manufacturers including Motorola, AT&T, Nortel, Ericsson, and IMM (Grant 2000).

A.38 In 1989, based on its commercial readiness and availability, the CTIA consortium initially settled on a technology which was similar to the European GSM standard. This private sector attempt at *de facto* standardization could potentially have recreated European high penetration rates in the US — although without regulatory oversight (Cabral 2009).

A.39 The initial technology was called Time Division Multiple Access (TDMA). TDMA allows several users to share the same frequency channel. It does so by dividing the signal into different time slots, and users transmit these time slots simultaneously allowing the entire frequency channel to be used by different users at the same time. However, in 1991 Qualcomm developed a competing technology called CDMA, (Code Driven Multiple Access). CDMA increases spectrum capacity by allowing all users to occupy all channels at the same time. Transmissions are spread over the whole radio band, and each voice or data call is assigned a unique code to differentiate from the other calls carried over the same spectrum.[13]

A.40 Several industry players judged Qualcomm's CDMA technology as superior to TDMA, and several operators began adopting CDMA instead of TDMA. In 1993, the CTIA published Qualcomm's CDMA technology as 'IS-95'. This resulted in the US market being divided between these two standards. By 2003, there was nearly equivalent nationwide coverage in the US for standards based on alternative technologies, i.e. CDMA and TDMA. This coverage was achieved without the FCC (or any other regulatory body) mandating a standard and without a mandate for nationwide roaming (Gandal et al. 2003).

Standard setting in Japan

A.41 The Japanese experience was of a government-mandated standard development that resulted in a proprietary standard that was prevalent only within Japan. The Japanese government, which still had a large influence through Nippon Telegraph and Telephone (NTT), mandated a standard called Personal Digital Cellular (PDC) (van de Kaa and Greeven 2016). In 1992, NTT started the first 2G service in Japan. This policy resulted in a proprietary system (belonging to NTT) which was widely adopted in Japan, but scarcely at all internationally.

Adoption of 2G standards in the rest of the world

A.42 Other countries did not develop their own standards but used either the GSM or the CDMA standards. For example, China did not take any part in the development of 2G technologies but used both the GSM and CDMA technologies starting in 1994.

13 ITU website: <http://www.itu.int/osg/spu/ni/3G/technology/>. See also Cabral (2009).

Table 1: Global subscribers by technology, March 1999

Technology	Countries
1G AMPS	95
1G NMT	35
1G TACS	24
2G GSM	129
2G PDC	1
2G CDMA	17
2G TDMA	36

Source: World Bank. Competition in Mobile Telecoms, August 1999

Table 2: Number of subscribers by 2G standard (millions)

	1993	1996	2000	2002
GSM	1	25	213	750
CDMA	-	1	72	120
TDMA	-	-	-	100

Source: Cabral (2009), Exhibit 1.

A.43 Table 1 shows the distribution of subscribers by technology. A large number of countries had multiple technologies, not just across generations, but even within generations. For example, consumers in India had access to both GSM and CDMA.

A.44 Table 2 shows the evolution of subscribers by 2G standards for selected years between 1993 and 2002.

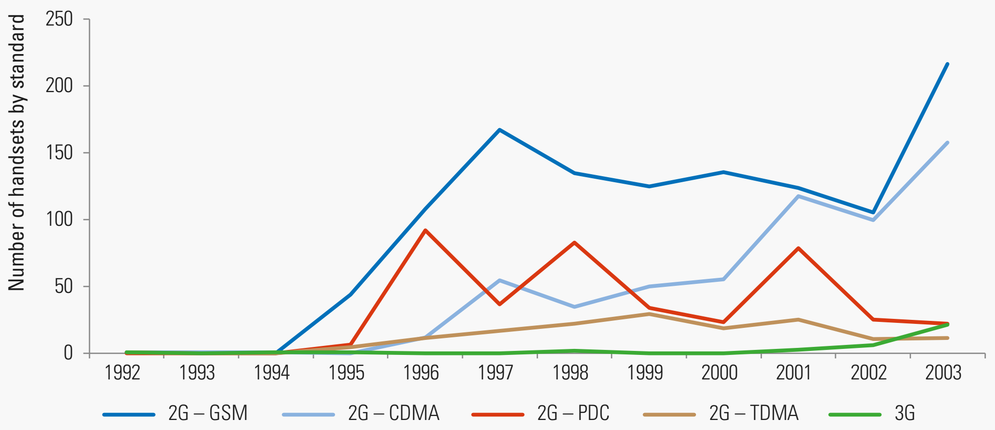
A.45 In 2002, GSM had more than three times the subscribers of TDMA and CDMA combined. However, the GSM standard was not superior. CDMA was believed to be technically more advanced than the technology employed in GSM by several industry players and offered more capacity, better call quality and more potential for services than GSM (Bach 2000; UK PC 2013).

The benefits of having a common standard

Comparing the development of the market in Europe and in the US

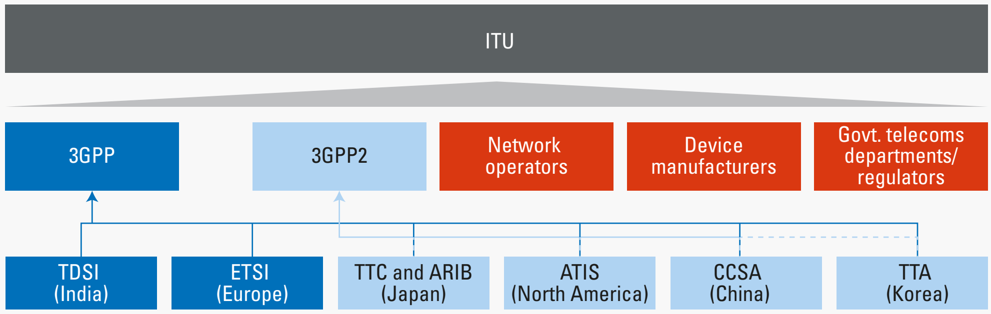
A.46 In the 1990s, Europe had a common standard for 2G telephony whereas the US had a fragmented market. Possibly as a result of this difference, adoption rates in the US were behind those in Europe in the 1990s. In June 2002, US mobile penetration rates had reached 40%; in Europe, most countries had by then surpassed the 70% threshold (Cabral 2009).

Figure 3: Introduction of new 2G handsets by standard, 1992-2003



Source: Adapted by CL from Koski and Kretschmer (2009), Figure 2.

Figure 4: Standard setting interactions between the ITU and its members



Source: Box A.2 and Box A.3.

A.47 Moreover, lacking a unified, sizeable market, device manufacturers found it difficult to take advantage of scale economies and produce affordable equipment. The US device manufacturers industry fell behind Europe's. In 1998, US sales of digital phones (of all technologies) first surpassed analogue phone sales (10.1 vs 7.9 million units); in Europe, by contrast, the tipping point occurred in 1995 — three years earlier (Cabral 2009).

A.48 Figure 3 shows the number of new handsets supporting different standards launched between the years 1992 and 2003, and thus reflects the relative commercial success different 2G standards.

A.49 The most handsets were introduced for the GSM standard during the 1990s, although in 2001 and 2002 there was a rise in the number of new CDMA handsets, and manufacturers introduced almost as many CDMA as GSM phones. The number of new TDMA handsets remained relatively low through the observed time period. The Japanese PDC standard took off rapidly but then declined.

A.50 The contrasting stories of GSM and CDMA illustrate a dilemma in standard-setting. A common standard can and normally will lead to more rapid adoption by consumers and manufacturers, but competing standards could allow better technology to emerge. Sometimes the dilemma is unavoidable, but broad-based Standard Development Organisations setting open standards are more likely to avoid it than government mandated or proprietary standards, as we discuss elsewhere in this paper.

Evolution of standard setting from 2G to 4G

The ITU-led standard setting process

A.51 Since the mid-1980s[14], the International Telecommunications Union (ITU), a United Nations specialized agency for information and communication technologies, had been coordinating efforts of government, industry and private sector in the development of a global broadband multimedia international mobile telecommunication system.[15] The aim was to address the needs for additional spectrum allocations and harmonised standards to improve interoperability.[16]

A.52 Until 1993, the ITU's role was limited to decisions on radio-frequency spectrum allocations for 2G services.[17] However, through the 1990s, the growing demand for global wireless communication and data services also increased the demand for additional spectrum and the need for interoperability.[18] In response to this, the ITU started coordinating efforts to develop standards called 'International Mobile Telecommunications' (IMT) standards in 1993. The ITU continues to lead international efforts to develop new generations of standards for global mobile communications, by facilitating cooperation among members through a streamlined process to develop standards.

ITU membership

A.53 As of 2016, ITU has more than 700 members from industry, international and regional organisations (including national regulators and telecoms authorities) as well as academia. Members can submit technical specifications to be included in standards, and all members have the opportunity to review the specifications and participate in the voting process. Two different partnerships of external organisations, 3GPP and 3GPP2, are tasked to define and maintain standards. Figure 4 illustrates these relationships and provides further details on 3GPP and 3GPP2 respectively. Device manufacturers and network operators are typically members of the ITU directly and indirectly through 3GPP or 3GPP2.

14 ITU website: <https://www.itu.int/osg/spu/imt-2000/technology.html>.

15 ITU website: <http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-adv/Pages/default.aspx>.

16 ITU website: <http://www.itu.int/en/about/Pages/whatwedo.aspx>.

17 ITU website: <http://itu150.org/historical-timeline/>.

18 ITU website: <http://www.itu.int/en/about/Pages/whatwedo.aspx>.

Box A.2: 3GPP

3GPP was formed in 1998 to develop a common wireless cellular system for Europe, Asia and North America. 3GPP is a consortium of telecommunications SSOs known as 'organisational partners'. These include:

- Japan's Association of Radio Industries and Businesses (ARIB);
- North America's Alliance for Telecommunications Industry Solutions (ATIS);
- China Communications Standards Association (CCSA);
- European Telecommunications Standards Institute (ETSI);
- Korea's Telecommunications Technology Association (TTA);
- India's Telecommunications Standards Development Society (TSDI); and
- Japan's TTC (Telecommunications Technology Committee). [19]

Voluntary member organisations include firms (such as Ericsson and Qualcomm).[20]

Unlike GSM but similar to ETSI, standard development efforts are led primarily by manufacturers and private operators. Supranational institutions focus on the provision of a forum for cooperative exchange and, as appropriate and desired, legal backing (Bach 2000).

3GPP has also seen increasing collaborations between groups of telecommunication associations from Japan, the USA, China, Europe, Korea and India (Van de Kaa and Greeven 2016).

Members participation and contribution

Qualcomm (2015) have analysed data on participation and contribution in 3GPP over the 2005 to 2012 period (inclusive). The number of contributions has increased from 13,991 in 2005 to 37,081 in 2012 reaching a peak of 50,519 in 2009. Roughly a third of the contributions are incorporated into releases. Membership of the 3GPP has increased since its inception until 2012, and in 2012 and participation in the working groups varied between 80 and 205 depending on the participants' interest in the area covered by the working group. Over the 2005-2012 period (inclusive) a total of 492 firms attended a 3GPP meeting, but only a few firms submit a majority of the contributions. The top 2% (i.e. 9 firms) were responsible for submitting 60% of all contributions.

Another group - with membership that partly overlapped with 3GPP - formed the 3rd Generation Partnership Project 2 (3GPP2) in 1999 to develop global specifications to represent North American and Asian interests.[21] The participating associations are:

- Japan's Association of Radio Industries and Businesses (ARIB);
- North America's Telecommunications Industry Association (TIA);
- China Communications Standards Association (CCSA);
- Korea's Telecommunications Technology Association (TTA); and
- Japan's TTC (Telecommunications Technology Committee).[22]

ETSI was not a member of the 3GPP2 group.

3GPP and 3GPP2 Standardisation process

A.54 The 3GPP standardisation work is contribution-driven. Companies ("individual members") participate through their membership of one of the participating associations. As of December 2016, 3GPP was composed of 535 individual members[23] and 3GPP2 was composed of 24 individual members.[24] The two partnerships comprise multiple Working Groups (WGs) which are organised into three Technical Specification Groups (TSGs).[25,26] The technology specifications are first decided within WGs and approved by the TSGs. Specifications are grouped into 'releases' which comprise standards. A release consists of a set of internally consistent set of features and specifications.[27]

19 3GPP website: <http://www.3gpp.org/about-3gpp/partners>.
20 ETSI website: <http://webapp.etsi.org/3gppmembership/Queryform.asp>.
21 3GPP2 website: <http://www.3gpp2.org/Public_html/Misc/AboutHome.cfm>.
22 3GPP2 website: <http://www.3gpp2.org/Public_html/Misc/PartnersHome.cfm>.
23 ETSI website: <http://webapp.etsi.org/3gppmembership/Results.asp?Member=ALL_PARTNERS&SortMember=Name&DirMember=ASC&SortPartner=Name&DirPartner=ASC&SortMarket=Name&DirMarket=ASC&SortObserver=Name&DirObserver=ASC&SortGuest=Name&DirGuest=ASC&Name=&search=Search>.
24 3GPP2 website: <http://www.3gpp2.org/Public_html/Misc/Memberindex.cfm?requesttimeout=30>.
25 3GPP website: <http://www.3gpp.org/about-3gpp/about-3gpp>.
26 3GPP website: <http://www.3gpp2.org/Public_html/Misc/AboutHome.cfm>.
27 3GPP website: <http://www.3gpp2.org/Public_html/Misc/AboutHome.cfm>.

ITU standardisation process

A.55 ITU members submit contributions to develop standards to a 'Study Group'. A Study Group is composed of other members who then review the contribution and approve the contribution as a study 'Question'. A 'Question' is the basic project within the ITU. While all members can submit contributions to the ITU, it is typically through 3GPP or 3GPP2.

A.56 To assist in the organisation of the work, the Study Group may be organized into a number of 'Working Parties'. It coordinates a number of study Questions on a related theme, e.g. the Media Coding Working Party in Study Group 16 deals with all study Questions relating to coding of speech, audio and video streams that are used for Internet calls, DVDs, etc.[28] Considering the text of the Question and guidance from the Study Group, the participants determine what Recommendations are required and develop text for these Recommendations taking all relevant inputs into account and consulting other relevant parts of ITU. The contribution is then drafted into a 'Recommendation' on which members are consulted, and following comments from members, approved as a standard. A recommendation is a set of guidelines, and is adopted on a voluntary basis by members.[29]

A.57 This was the process followed by the ITU for setting standards for 3G ('IMT-2000') and 4G ('IMT-Advanced').

Transition from 2G to 3G

A.58 By the late 1990s, the telecoms industry had already begun developing specifications for the third generation (3G) of mobile systems, which would go beyond voice communications and deliver improved data based services and would provide substantially increased data transfer rates.

A.59 The main difference between 3G and 2G technology is the use of 'packet switching' in 3G systems as opposed to 'circuit switching' in 2G systems for data transmission alone. Both systems used 'circuit-switching' for voice services. Packet-switched networks move data in separate, small blocks, i.e. packets, based on the destination address in each packet. When received, packets are reassembled in the proper sequence to make up the message. Circuit-switched networks require dedicated point-to-point connections during calls. Therefore, packet switching is considered more efficient (Computer World 2017).

A.60 3G was expected to provide higher data transmission rates compared to 2G. Data rates in 3G were expected to be 348 Kbps (moving) to 2 Mbps (stationary) in 2005.[30] However, 3G standards were updated constantly, with the data speeds increasing with subsequent releases (see Figure 5).

A.61 The ITU developed a set of specifications for 3G under the title of 'International Mobile Telecommunications-2000' (IMT-2000).[31] 3GPP was the standard body behind the 'Universal Mobile Telecommunications System' (UMTS) developed by Nokia that was an upgrade to GSM (2G) networks in Europe but was not compatible with the existing infrastructure. While this was based on the existing core GSM technologies, it incorporated a wideband-CDMA technology (W-CDMA).

A.62 Inferior standards can persist simply because of the legacy they have built up ('path dependence')[32]. In spite of GSM's success in 2G, 3GPP was keen on the W-CDMA standard despite the infrastructure changes required. Being locked in to the old GSM standard would have led to outcomes that were too costly to change later (Lee et al. 2009). 3GPP2 was the standard body behind the competing 3G standard 'CDMA2000' which was developed by US network providers and was compatible with the existing infrastructure.

A.63 The proponents of the two standards were not able to agree on a single standard, so the two standards were developed in parallel. As participants failed to reach a compromise on IMT-2000, it appeared that worldwide network incompatibility for 2G would be carried over into 3G technology.

A.64 A coalition of network providers called the 'Operators Harmonization Group' (OHG)[33] succeeded in securing a compromise between the competing camps. Rather than adopting a single standard for IMT-2000, a coalition of operators and manufacturers proposed to base 3G equipment on an umbrella standard with three nodes for the three alternative technologies. 3G handsets were required to be able to function in any network employing one of the standards of the 3G 'family' (Bach 2000).

28 ITU website: <http://www.itu.int/en/ITU-T/about/Pages/development.aspx>.
29 ITU website: <http://www.itu.int/en/ITU-T/about/Pages/approval.aspx>.

30 ITU website: <http://www.itu.int/osg/spu/ni/3G/technology/#Cellular Standards for the Third Generation>.
31 ITU website: <https://www.itu.int/osg/spu/imt-2000/technology.html>.
32 As we discuss in Section 3.
33 The OHG founding members included Bell Atlantic Mobile, Bell Mobility, BellSouth Cellular, China Mobile, China Unicom, DACOM, DDI, Hansol M.Com, IDO, Japan Telecom, KDD, Korea Telecom, LG TeleCom, Microcell Connexions, NTT DoCoMo, Omnitel, SingTel, SK Telecom, Sprint PCS, Telefonica Moviles, Telesystem International Wireless, T-Mobil, Vodafone AirTouch, and VoiceStream Wireless. (Source: 3GPP2 website: http://www.3gpp2.org/Public_html/News/OHGLetter.cfm, as accessed on 23 January 2017)

Box A.4: 2G and 3G standard setting in Korea

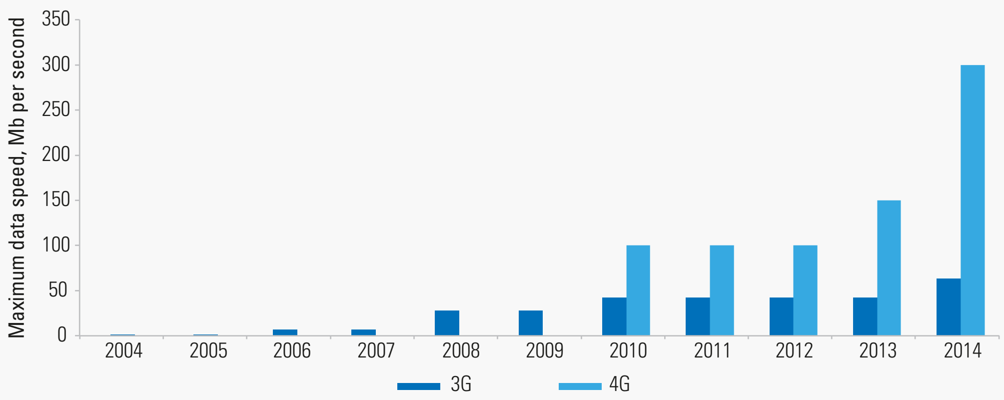
At the beginning of the 1990s, Korea had a single mobile phone operator. Less than 5% of the population had access to mobile phone services, most of them using phones and network devices predominantly manufactured by foreign companies. By the 2000s, over 75% of the population had access and several companies (e.g. Samsung Electronics, LG Electronic) were successfully competing in the global mobile industry.

In Korea, the government adopted Qualcomm's CDMA as the standard for 2G mobile telephony. This brought the Korean market together and helped Korean handset manufacturers flourish. Qualcomm needed partners to transfer technological knowledge to the field, and the Korean government thought this would give its national manufacturers an advantage against their foreign counterparts. As expected by the government, Korean telecom manufacturers became leaders in CDMA technology. Samsung, one of Korea's major telecom manufacturers, made great strides against its global competitors and by 2003 had established primacy in CDMA handset markets.

However, as the mobile market developed further, the selection process involving 3G technology standards led to serious disputes between the government and network operators: Korean network operators wanted to adopt W-CDMA while the government insisted on at least one CDMA2000-based service. The W-CDMA technology was widely accepted globally whereas the CDMA2000 technology, favoured by the government, would signal political success as it was an advanced version of CDMA. The Korean government attempted to force CDMA2000 against the network operators' wishes and took action to secure the competitiveness of Korean manufacturers in the equipment export market, using CDMA technology. The government therefore stepped away from mandating a standard, even if all operators preferred the W-CDMA, and instead ensured the availability of multiple standards by convincing one of the operators to adopt CDMA2000 instead of W-CDMA.

The Korean experience illustrates that governments can help achieve coordination in markets with emerging technology, but may not be flexible enough to respond to the needs of a market with dynamic, evolving technologies.[34]

Figure 5: Data rates (Megabits per second), 2004-2015



Source: Adapted by CL from Gupta (2014), Figure 2.

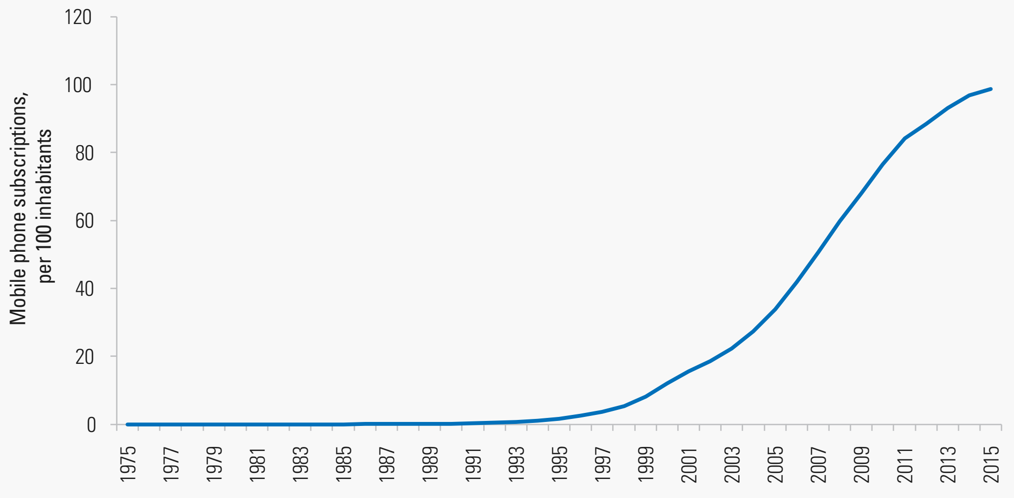
A.65 Despite the need for additional infrastructure, investments in new 3G technology appear to have been worth it. Deloitte (2012) attempted to measure the effects of switching from 2G mobile wireless to 3G. They found that a 10 percent increase in internet penetration, in the form of a switch from 2G for 3G, correlated with an average increase of GDP of 0.15 per cent in a group of 96 countries. Furthermore, adding 3G connections seemed to be more beneficial for countries with low 3G penetration. A doubling of mobile data use is associated with an increase in GDP per capita of 0.5%.

Transition from 3G to 4G

A.66 3GPP developed the LTE-Advanced standard which was proposed as an upgrade to the 2G and 3G networks.[35] The IEEE (Institute for Electrical and Electronic Engineers) and the Chinese Ministry of Industry and Information Technology also developed technologies that were IMT-Advanced compliant.[36] Standardization for 4G standards thus became a process whereby standards were developed partly by official bodies (IEEE), partly by forums (3GPP), and partly by governmental agencies (MIIT).[37]

34 Yoo et al (2003) and Jho (2007)
35 Van de Kaa and Greeven (2016), Section 5.4.
36 Van de Kaa and Greeven (2016), Section 5.4.
37 Van de Kaa and Greeven (2016), Section 5.4.

Figure 6: Mobile cellular subscriptions per 100 inhabitants, 1975 to 2015



Source: World Bank Database <http://data.worldbank.org/indicator/IT.CEL.SETS.P2>

A.67 3GPP's LTE-Advanced system formed the basis of the ITU IMT-Advanced which provide a wide range of additional services beyond those in IMT-2000. These standards were approved in 2008[38] and formed the standards for 4G.

A.68 The main difference between 3G and 4G is that 4G eliminates 'circuit switching' and uses 'packet switching' for both voice and data transmission. Data rates in 4G were required to be 100 Mbps (high mobility) to 1 Gbps (low mobility).[39] In contrast, data rates in 3G were expected to be 348 Kbps (moving) to 2 Mbps (stationary).[40] As with 3G standards, subsequent updates to the standard have resulted in increased internet speeds as shown in Figure 5.

A.69 The introduction of 4G required the rollout of 4G-specific networks. Operator investments totalled around $880 billion between 2011 and 2015, with mobile broadband and LTE network deployments a key driver.[41]

38 ITU website: http://www.itu.int/pub/R-REP-M.2134-2008, as accessed on 26 January 2017.
39 ITU website: http://www.itu.int/pub/R-REP-M.2134-2008/en, as accessed on 04 Jan 2017.
40 ITU website: http://www.itu.int/osg/spu/ni/3G/technology/#Cellular Standards for the Third Generation, as accessed on 04 Jan 2017.
41 GSMA (2016), page 3.

The evolution of the mobile telephony ecosystem

A.70 Declining usage costs as well as infrastructure development costs have made mobile telephony increasingly more accessible, as shown in Figure 6. At the end of 2015, there were 4.7 billion unique mobile subscribers globally, a subscriber penetration rate of 63%, with regional penetration rates ranging from 43% in Sub-Saharan Africa to 85% in Europe[42]. Overall subscriber growth rates slowed in 2016, due to saturation in developed markets and the difficulties of connecting low-income populations in developing markets.[43]

A.71 Total Internet traffic has experienced rapid growth in the past two decades. More than 20 years ago, in 1992, global Internet networks carried approximately 100 GB of traffic per day. Ten years later, in 2002, global Internet traffic amounted to 100 gigabytes per second (GBps). In 2015, global Internet traffic reached more than 20,000 GBps. Table 3 provides some benchmarks for total Internet traffic.

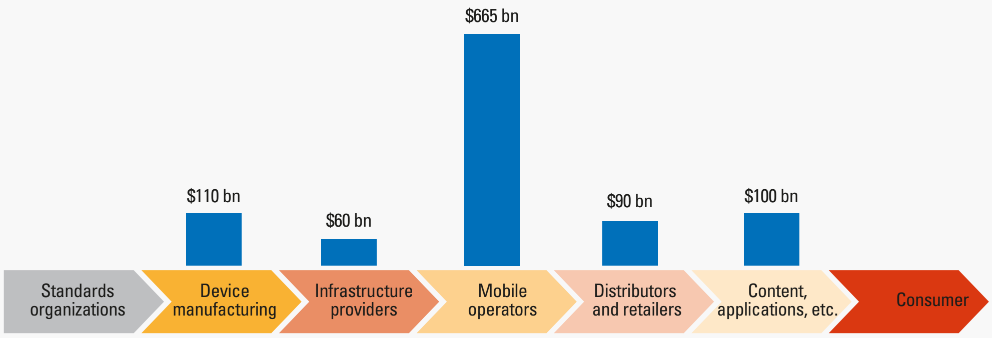
42 GSMA (2016), page 8.
43 GSMA (2016), page 2.

Table 3: Internet traffic carried by global networks, 1992-2020

Year	Global Internet Traffic
1992	100 GB per day
1997	100 GB per hour
2002	100 GBps
2007	2,000 GBps
2015	20,235 GBps
2020 (forecast)	61,386 GBps

Source: Cisco VNI, 2016. <http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html>

Figure 7: Direct economic contribution of the mobile ecosystem (USD billions), 2016



Notes: Economic contribution figures based on GSMA (2016) 'The Mobile Economy 2016'
Source: GSMA (2016)

Elements of the mobile ecosystem

Direct economic contribution

A.72 Figure 7 shows the various elements of the mobile ecosystem[44] and their direct contribution[45] to the economy. The direct contribution from mobile operators in 2015 was $675 billion in economic value added terms, or 0.9% of the world's GDP. Beyond mobile operators, the mobile ecosystem generated an additional economic value added of more than $450 billion, or approximately 0.6% of global GDP.[46]

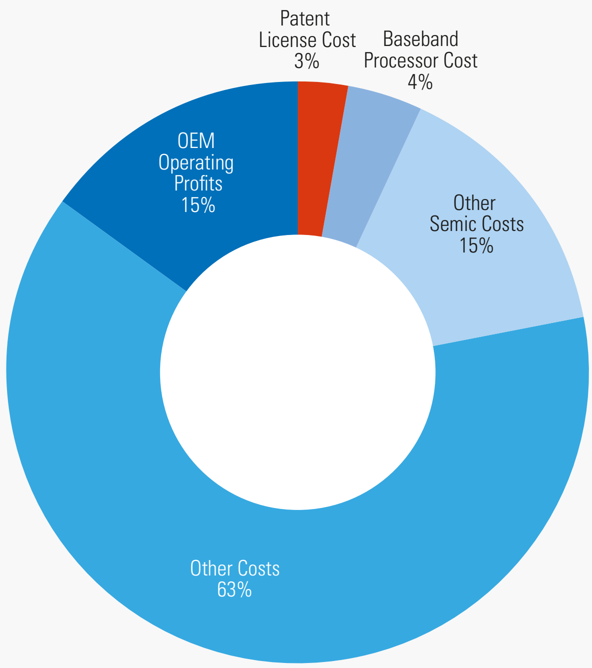
A.73 In 2015, GSMA estimated that mobile telephony and associated industries generated 4.2% of global GDP, a contribution that amounts to more than $3.1 trillion of economic value added. In addition, these industries directly provided employment to nearly 17 million people across the world, and indirectly supported an additional 15 million jobs in other sectors of the world economy. The industry also contributed $430 billion in general taxation, with a further $90 billion paid through spectrum auctions.[47]

Revenues

A.74 Mobile phone revenues in 2015 were USD 437 billion, of which USD 14 billion, i.e. 3.3%, were paid as patent licence costs. Figure 8 below shows the breakdown of revenues into costs and operating profits for 2015. Operating profits of the industry were 15% of revenues whereas costs were 86% of revenue, of which patent costs were only 3.3% of revenue.

A.75 Mobile phone revenues and licensing revenues have increased by about the same amount - 11% and 9% respectively per year between 2007 and 2015 - so the share of licensing revenues of total mobile phone revenues has remained constant at around 2.5% between 2009 and 2015.[48] Figure 9 opposite shows the distribution of mobile phone licencing revenues by year. The HHI (measuring how concentrated is ownership of patents) has declined by close to a quarter of its level in 2007. The share of the top five firms (C5) has remained essentially steady.

Figure 8: Mobile phone revenues and costs estimates, 2015



Notes: Total mobile phone revenues in 2015 were USD 437 billion, of which operating profits were USD 65.1 billion, patent licence costs were USD 14.4 billion, baseband processor costs were USD 16.2 billion, other semiconductor costs were USD 67.7 billion, and all other costs were USD 273.6 billion.
Source: Adapted by CL from Galetovic et al. (2016), Figure 2.

44 In addition to the standards organisations and consumers, the mobile ecosystem includes infrastructure service providers, retailers and distributors of mobile products and services, device manufacturers (mobile phones, tablets and wearables), and providers of mobile content, applications and services.

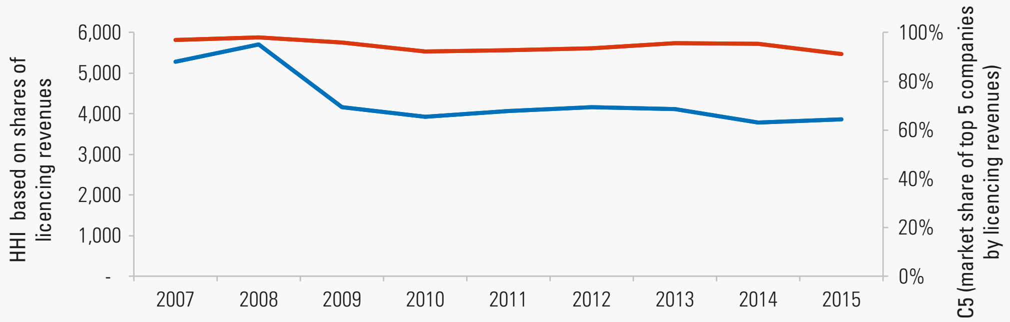
45 The direct economic contribution to GDP of mobile operators and the mobile ecosystem by adding the economic value added generated by companies operating in the sector across 236 countries and territories. Economic value added is calculated as the difference between the value of sales made by the sector and the direct cost of making those sales.

46 GSMA (2016), page 21.

47 GSMA (2016), page 3.

48 We choose 2009 as the year of comparison as data on licensing firms is available based on a consistent sample from 2009 onwards in the Galetovic et al. (2016) dataset.

Figure 9: HHI and C5, Share of mobile phone patent licencing revenues, 2007-2015



Source: CL analysis using data from Galetovic et al. (2016).

Table 4: SEP licencing fee and royalty yields, 2014

Year	Revenues (USD)	Yield (% of total 2014 handset revenues)
Major SEP owners with licensing programmes: Alcatel-Lucent, Ericsson, Nokia, InterDigital, Qualcomm	10.6 billion	2.6%
Patent pools: SIPRA (WCDMA), Via Licensing (LTE), Sisvel (LTE)	Less than 4 billion	Less than 1%
Others: including Apple, Huawei, RIM, Samsung, LG	Less than 6 billion	Less than 1.5%
Total	Approx. 20 billion	Approx. 5%

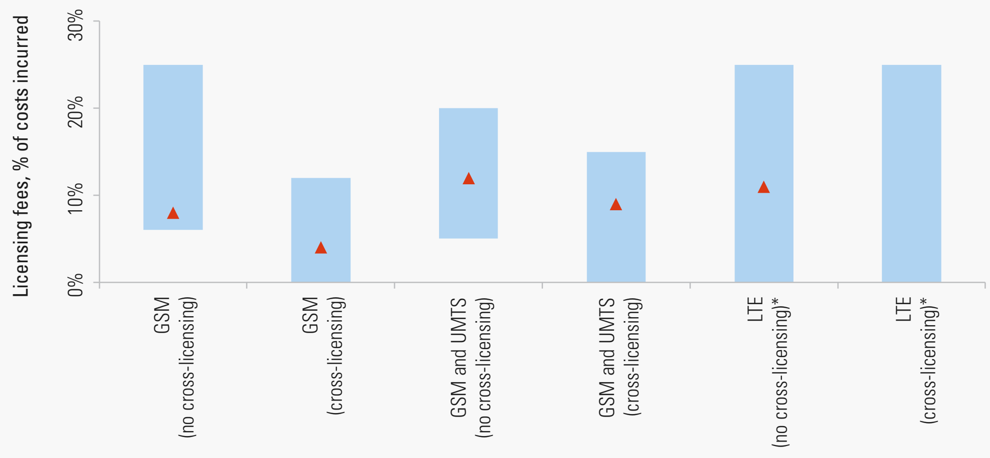
Notes: Yields are total licensing fee revenues including lump sums and running royalties as a percentage of $410 billion in total global handset revenues
Source: Mallinson (2016), Page 7.

A.76 As we discuss in Section 4, an important driver of this industry is the 'market for technology' yet license fees to IPR-holders constitute only a small part of the total cost to the consumer. Estimates by Mallinson (2015) show licensing revenues of significant mobile-SEP licensors and other public sources including patent-pool rate-card charges. These figures, shown in Table 4 below, indicate that the total royalties paid, including lump sums and running royalties, for standard-essential 2G, 3G and 4G technologies amount to approximately $20 billion per year. Similarly, around 10.4% of the build cost of a Nokia N95 phone was estimated to be paid as licence fees, around 4% of the final price (Ali-Yrkko et al. 2011).[49]

A.77 Licensing fees typically range between 10% and 25% of the costs of the corresponding device. Figure 10 shows the range of licensing fees for mobile devices as well as typical licensing fees, expressed as a percentage of the wholesale value of the terminal.

49 Note that these fees will exclude 'internal' use of IPR or any swap arrangements under which patent owners licence one another royalty-free.

Figure 10: Licensing fees, % of costs incurred



Source: Adapted by CL from Blind et al. (2011), Figure 4-2.

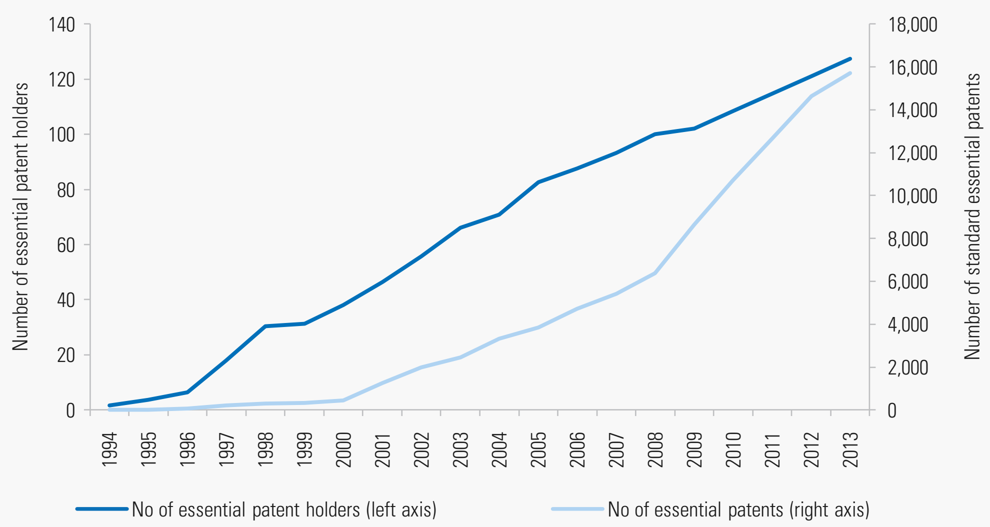
Evolution of the ecosystem

A.78 The mobile ecosystem consists both of technology innovators and manufacturers, working together in 'markets for technology'. It is dynamic with many new and start-up companies entering the sector. Between 2009 and 2014, venture capital investments in mobile have doubled as a percentage of total venture capital investments, reaching 8% ($37 billion) in 2014.[50]

A.79 In the following paragraphs, we use estimates from various sources showing that increasing numbers of patents have been accompanied by an increase in the number of firms, so overall concentration of ownership of technology in the standards has decreased. The number of SEP holders for the widely deployed 2G, 3G, and 4G wireless cellular standards grew from 2 in 1994 to 130 in 2013, as shown in Figure 11. The market for device manufacture has also evolved in response to the changing technological environment, as shown in Figure 12.

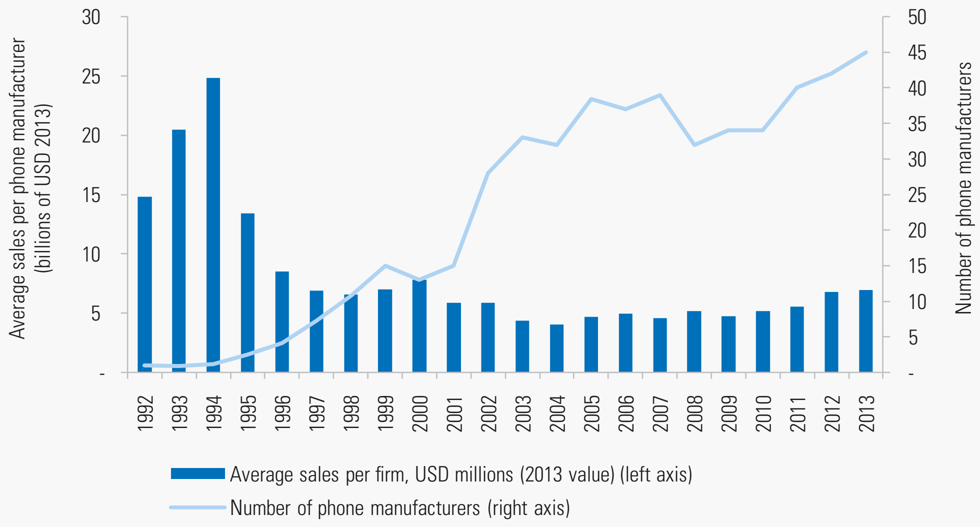
50 BCG (2015), page 7.

Figure 11: Number of SEPs and SEP holders, 1994-2013



Source: Adapted by CL from Galetovic and Gupta (2016), Figure 2.

Figure 12: Average sales per phone manufacturer and unique phone manufacturers, 1994-2013



Source: Adapted by CL from Galetovic and Gupta (2016), Figure 9.

A.80 Bekkers and West (2009) compare patenting activity in ETSI's GSM program (finalized in 1990) with its subsequent UMTS standardization program (finalized in 1999). They find:

a. an eightfold increase in the number of disclosed essential patents for UMTS (1,227) over GSM (140);

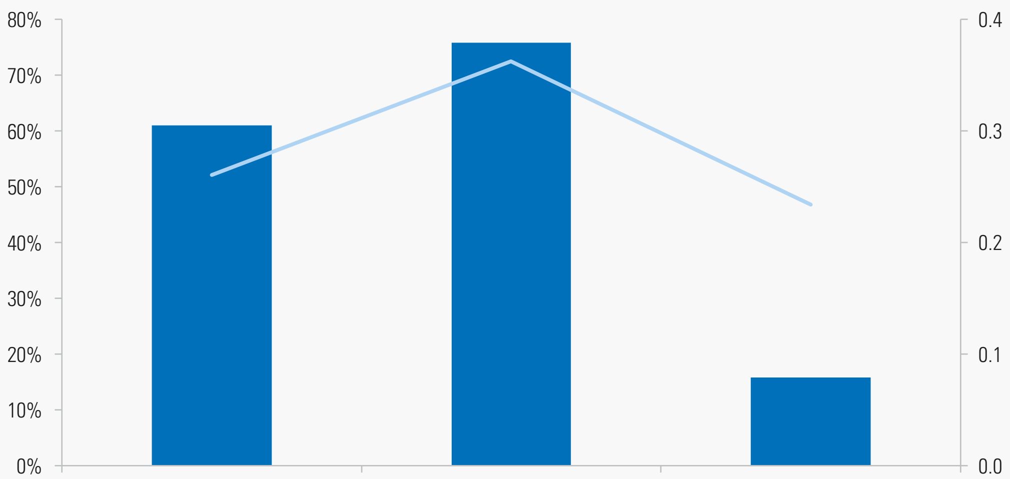
b. a threefold increase in the number of patent holders (23 to 72); and yet

c. firm-level concentration of patents decreased substantially between the (2G) GSM and (3G) UMTS projects, with CR4 concentration ratios increasing from 52% for GSM to 72% for UMTS, and CR8 ratios increasing from 73% for GSM to 92% for UMTS.

A.81 A different survey by Caviggioli et al. (2015) finds that concentration has decreased over time; the CR4[51] concentration ratio has declined from 72.4% for (3G) UMTS standards to 46.8% for (4G) LTE standards, as shown in Figure 13.

51 CR4, or Top-4 Concentration Ratio, is the combined market share of the top-4 firms.

Figure 13: Concentration of declared inventions across patent owners



Notes Concentration is measured using 'CR4' which represents the sum of shares of the top four companies and the Herfindahl Hirschman Index (HHI) which represents the sum of the squares of the market sharesof all companies. Higher values indicate higher concentration levels.

Source: Adapted by CL from Caviggioli et al. (2015), Table 3.

Table 5: R&D – shares of inventions in standards

SEP owning entities	No. and (%) of 2G inventions	No. and (%) of 3G inventions	No. and (%) of 4G inventions
Top 2	1,208 (42%)	2,188 (30%)	2,424 (23%)
Top 5	1,951 (69%)	4,197 (58%)	5,125 (48%)
Top 10	2,385 (84%)	5,616 (78%)	7,664 (72%)
Top 20	2,648 (93%)	6,524 (90%)	9,708 (91%)
Top 40	2,802 (99%)	7,088 (98%)	10,476 (99%)

Source: Padilla and Llobet (2016).

A.82 The share of the top 2, top 5 and top 10 firms' share of inventions is lower for 4G than for 3G and for 2G. Table 5 below shows the number of SEPs and the share of total SEPs at various levels.

A.83 For 2G and 3G patents, based on data from the USPTO, as published in 2013 by iRunway, Ericsson, Nokia and Qualcomm were the top three patent holders (Table 6). However, for 4G patents, as of 2013, Samsung, Qualcomm and Panasonic were the top three patent holders (Table 7).

A.84 The wide prevalence of the GSM standard may have allowed Ericsson and Nokia to dominate 2G and 3G patents. However, with the adoption of a more global standard with 3G, non-European firms such as Samsung and Panasonic have been able to contribute more.

Table 6: Top 2G and 3G patent holders, 2012

Company name	Count of all 2G and 3G patients	Share of all 2G and 3G patents
Ericsson	1504	8.71%
Nokia	1363	7.89%
Qualcomm	915	5.30%
Alcatel-Lucent	793	4.59%
Samsung	653	3.78%
Research in Motion	598	3.46%
LG	584	3.38%
Cisco	488	2.83%
InterDigital	462	2.68%
Nortel Networks	346	2.00%
Broadcom	309	1.79%
Nokia Siemens Networks	173	1.00%
Siemens	144	0.83%
Sony Corp	121	0.70%
Vringo Infrastructure Inc.	74	0.43%
Philips Electronics	47	0.27%
France Telecom	45	0.26%
General Dynamics	34	0.20%

Source: i-Runway, <http://www.i-runway.com/images/pdf/iRunway%20-%202G%20and%203G%20Mobile%20Communication.pdf>.

Table 7: Top 4G patent holders, 2012

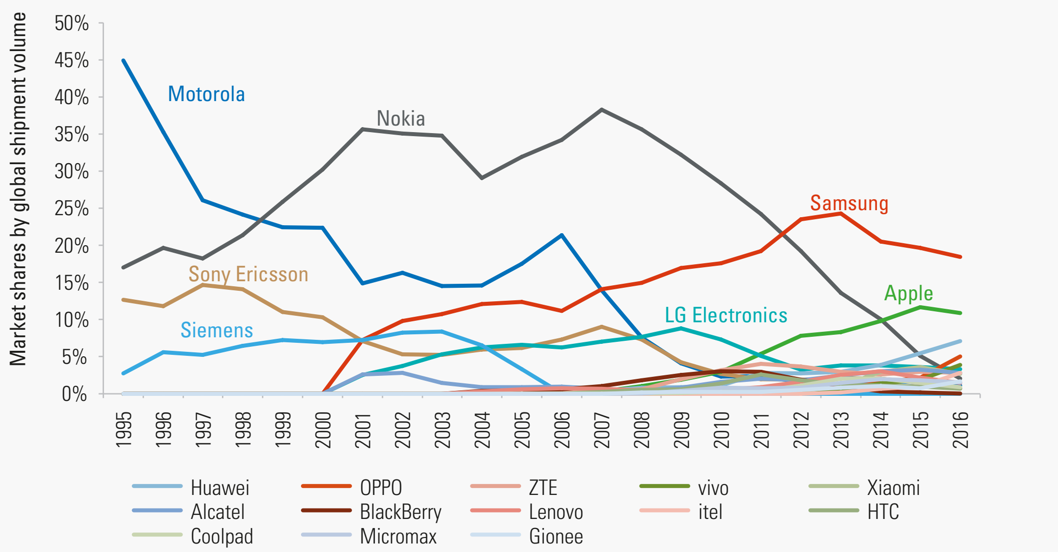
Company name	Count of all 4G patients	Share of all 4G patents
Samsung	1177	9.36%
Qualcomm	710	5.65%
Panasonic Corporation	389	3.10%
Interdigital	336	2.67%
Nokia Corporation	293	2.33%
Ericsson	247	1.97%
LG Corp.	224	1.78%
Motorola Solutions	192	1.53%
Motorola Mobility Holdings	32	0.25%
Sony Corporation	189	1.50%
NEC America Inc.	180	1.43%
Texas instruments	173	1.38%
Harris Corporation	160	1.27%
Nortel networks Corporation	152	1.21%
Intel Corporation	145	1.15%

Source: i-Runway, < http://www.i-runway.com/images/pdf/iRunway%20-%20Patent%20&%20Landscape%20Analysis%20of%204G-LTE.pdf >.

A.85 This decreased concentration in ownership of technology has been accompanied by decreased concentration 'downstream' in handset manufacture. The number of unique firms offering mobile wireless devices has grown steadily from 15 brands in 2000 to 45 in 2013. A total of 87 unique manufacturers were identified in the 2000 to 2013 period. This indicates that the market is dynamic with a large number of firms entering and leaving the market for mobile devices (Gupta 2014).

A.86 The dynamics of the handset market also illustrate its competitiveness, with leaders rising and falling (Figure 14). In the beginning of the 1990s, during the initial stages of the industry evolution, Motorola lost its position as the largest manufacturer to Nokia. However, after 14 years of being the market leader, Nokia lost its position to Samsung. In recent years, manufacturers such as Huawei and Xiaomi have risen to become among the largest device manufacturers.

Figure 14: Global market shares of handset manufacturers, 1995 to 2016



Notes: Sony Ericsson data also includes sales of Ericsson (1995-2001) and Sony (2012-2016).Manufacturers with largest market shares indicated on the chart; legend only includes smaller manufacturers.

Source: 1995-2003 sales are from Strategy Analytics and 2004-2016 sales are from IDC Worldwide Quarterly Mobile Phone Tracker.

Another important feature is the increasing competition in the market place starting around 2005, with many firms holding small market shares as opposed to a handful of big players.

A.87 In the early 1990s, Motorola was the market leader among device manufacturers and held a strong patent portfolio.[52] However, during the shift to digital communications in the 1990s, Motorola not only ignored the digital transition, it continued to build its own communications infrastructure called the 'Iridium project'. In contrast, Nokia was aggressive in introducing new products conforming to digital standards, and innovated to meet varying and evolving customer needs.[53]

52 Bekkers et al (2002).
53 Giachetti (2016), pages 57-63.

A.88 Similarly, in the 2000s, Samsung took advantage of the shift to smartphones and innovated aggressively to challenge and take over from Nokia as the market leader, who in turn, reacted slowly.[54] Early success by Blackberry among high-end professionals, was not sustained in the face of new challengers such as Apple and Google, as it was locked-in to its own operating system and did not react to evolving consumer preferences in time.[55]

54 Giachetti (2016), pages 55-66.
55 The Verge, 'Research, no motion. How the Blackberry CEOs lost an empire', 21 February 2012. Website: http://www.theverge.com/2012/2/21/2789676/rim-blackberry-mike-lazaridis-jim-balsillie-lost-empire#section-link-title5, as accessed on 23 January 2017.

Box A.5: Domestic standards and mobile phone manufacturing

Funk (2000) argues that the success of firms (defined in terms of market share) in the mobile communications market is strongly related to the evolution of standards. In each generation of technology, the most successful firms are from countries or regions whose mobile communication systems become world-wide standards.

The study finds evidence that North American firms were successful in the provision of services and infrastructure based on the North American 1G standards (AMPS/TACS) whereas Scandinavian firms were successful in the provision of services and infrastructure based on the Scandinavian NMT standard.

Similarly, for 2G, Scandinavian companies were the most successful for GSM-based products; North American firms were the most successful for TDMA-based products; and Japanese firms for PDC-based products.

Table 8: Domestic bias in mobile phone subscriptions and sales, 1990s

Standard	Subscribers connected to infrastructure belonging to a domestic firm for the standard	Phone sales by a domestic firm for the standard
AMTS	60%	70%
TACS	70%	50%
NMT	98%	55%
NTT	100%	100%
GSM	98%	60%
PDC	80%	95%

Notes: No specific date provided, figures relate to late 1990s.
Source: Funk (1998), Table 4.

Table 8 shows the market shares in infrastructure and phones for firms for whom the standard is a domestic standard. The domestic firms have between 50 and 100% of the market. The success of firms in standards for whom the standard is a domestic standard implies that the evolution of world-wide standards has a large effect on world-wide market shares.

The increase in Samsung's market share relative to that of Nokia and Ericsson at the turn of the century can be attributed to the adoption of a worldwide standard. The change in shares is even more pronounced in infrastructure than in phones.

A.89 Open standards allow small firms to contribute effectively to standards and participate in an industry without having to build their presence across the supply chain. For example, Neul, a small company with less than 200 employees founded in 2010, was a major contributor to 'Weightless' standards. 'Weightless' is a set of open standards developed by a Special Interest Group comprising 1400 members including large firms such as Qualcomm and Huawei. The 'weightless' standards govern the communication between devices, i.e. the 'Internet of Things' (IoT) which forms the basis of the fifth generation of mobile telephony, i.e 5G. In 2013, Neul produced a chip which was the first implementation of 'weightless' standards. Neul was acquired by Huawei in 2014.

A.90 Another example is that of Magnolia Broadband. Magnolia Broadband (founded in 2000) has developed "Beam Forming" radio frequency solutions for 3GPP standards, and has over 100 patents granted or pending. Its technologies, such as 'Beam Forming' help wireless network operators meet the increasing demand for wireless bandwidth. In 2012, Google acquired over 50 patents in Magnolia Broadband's portfolio. It continues to contribute to mobile telephony standards in a significant way.

Average price of mobile telephony

A.91 The 'quality-adjusted price' index for mobile devices decreased at 7% per year, compared to 2.3% per year in non-SEP industries. The average price of smartphones decreased by 22% between 2008 and 2013 (Gupta 2014). Figure 15 compares the quality-adjusted prices of telephone equipment with other standards-based industries, and shows that the early mobile phone innovation did not show typical performance of a 'standards-based' industry.

A.92 Until 1982, local telephone services in the United States were provided by a single company, AT&T, which leased telephones made by its Western Electric subsidiary to businesses and households. During the period before 1982, the quality-adjusted, relative price of phone equipment was declining at a steady rate.

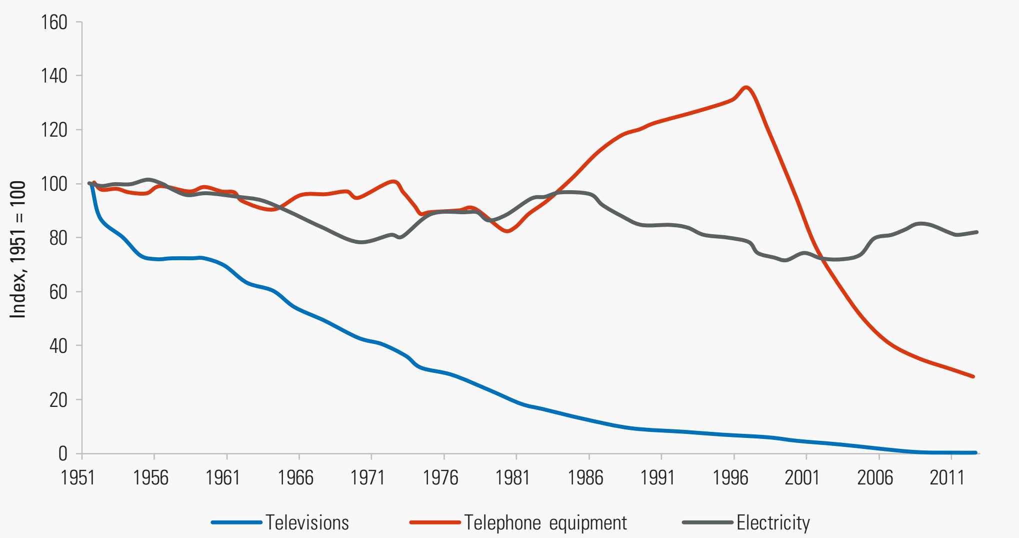
A.93 This pattern reversed in the 1980s when the first mobile phones—all produced by a single manufacturer, Motorola—entered the U.S. market. Motorola's initial product, the DynaTAC 8000X, had a price of $3,995 (about $9,400 in 2015 dollars), weighed more than a kilo, and had a battery life of a half hour.

A.94 The quality-adjusted relative prices of phones continued to climb until 1997. Around that time, Motorola's dominance was challenged by multiple manufacturers of 2G cell phones competing for market share. From that point onwards, and through both the 3G and 4G revolutions, the price of telephone equipment fell by 10 percent per year.

A.95 Consumer prices for devices have been declining in mobile telephony despite continuous advances in technology which have improved the consumers' experience. The introductory average selling price of successive generations fell between 1994 and 2013 (Figure 16). The average mobile subscriber costs have decreased 99 percent between 2005 and 2014. Infrastructure costs have declined dramatically – costs per megabyte transmitted declined by 95% during the transition from 2G to 3G and by a further 67% during the transition from 3G to 4G (Figure 17) while 4G data transmission speeds are 12,000 times higher compared to 2G.[56]

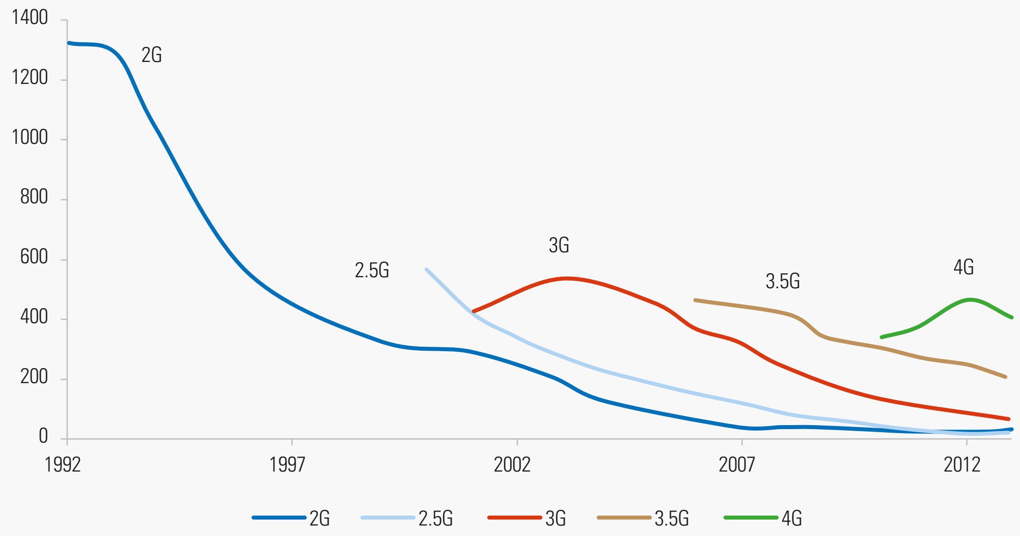
56 BCG Mobile Revolution (2015), page 4.

Figure 15: Quality-adjusted relative prices of telephone equipment, TVs and electricity (US data), 1951–2013



Source: Adapted by CL from Galetovic et al. (2015), Figure 5.

Figure 16: Average selling price of devices, USD (2013 prices), 1992-2013



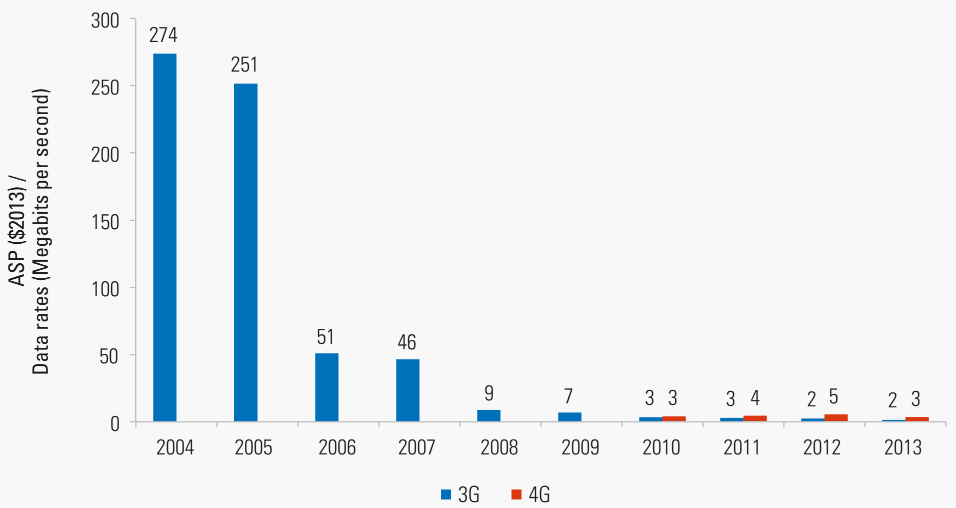
Source: Adapted by CL from Galetovic and Gupta (2016), Figure 8.

A.96 GSMA estimates that the effective price per minute has declined by 63% in the 10 years from 2004 to 2014.[57] A different measure of mobile market prices is the average revenue per user in the retail mobile market, which declined in the EU from € 221 in 2010 to € 169 in 2014.[58] Furthermore, the average selling price of handsets utilising 3G and 4G technology, divided by one measure of quality –maximum data download rates - dropped by 99% in just nine years from 2004-2013.

57 GSMA (2014).

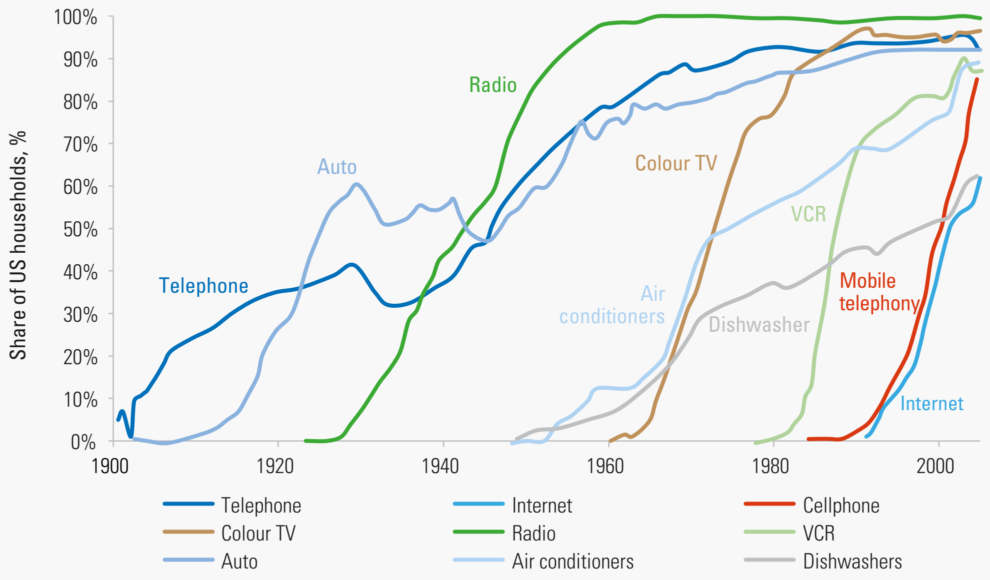
58 European Commission (Digital Single market), <http://digital-agenda-data.eu/datasets/digital_agenda_scoreboard_key_indicators/visualizations>. (Indicator Group: Mobile market. Indicator: Average Revenue per User (ARPU) in the Retail Mobile Market. Selected countries: European Union.

Figure 17: Cost of mobile telephones per data download speed ($2013/Megabits/s)



Source: Average selling prices of handsets deploying each technology: Galetovic and Gupta (2016), Figure 8. Maximum download data rates for each technology: Gupta (2015), Figure 2.

Figure 18: Technology adoption rates



Source: Adapted by CL from Felton (2008), as cited in McGrath (2013).

Mobile technology adoption rates

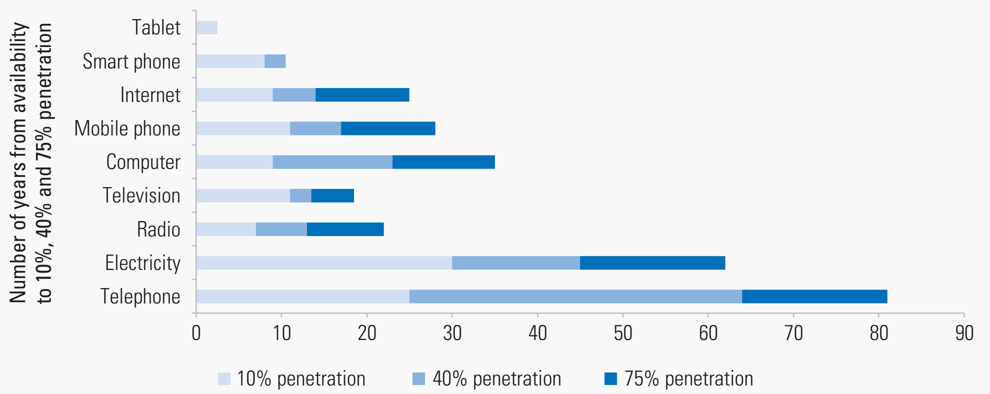
A.97 The rapid growth in telecoms subscribers, accompanied by the dynamism in the ecosystem, has made mobile technology one of the most rapidly adopted technologies in history. Figure 18 below, shows how long it took various categories of products, from radio to the Internet, to achieve different penetration levels in US households. It took several decades for the telephone to reach 50% of households, beginning before 1900. It took a single decade for cell phones to accomplish the same penetration in 1990.

A.98 There is clearly a general trend towards faster adoption, but the radio and TV industries also showed faster adoption than several more modern inventions, so there is more to this than merely a quickening pace of change.

A.99 Figure 19 depicts that the adoption of mobile telephony, especially smartphones, is much quicker than other technology-based industries. It took 30 years for electricity and 25 years for telephones to reach 10% adoption but less than five years for tablet devices to achieve the 10% rate. It took an additional 39 years for telephones to reach 40% penetration. Smart phones, on the other hand, accomplished a 40% penetration rate in just 10 years starting with 2002.

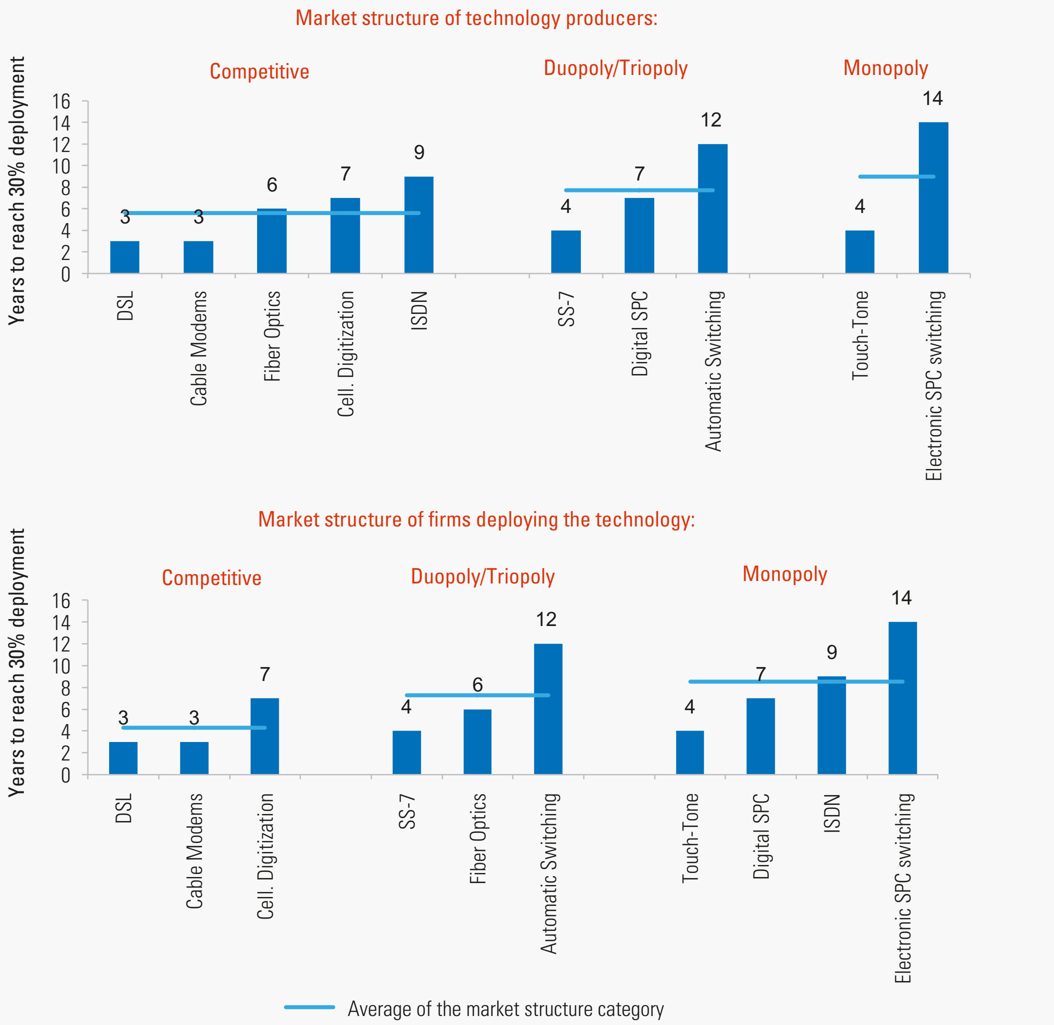
A.100 In a high-level review of 10 telecommunications technologies in the US, Shelanski (2000) found a positive correlation between the pace of deployment and market structures, with quicker deployment being associated with more competitive markets. Figure 20 shows the deployment times for the different technologies classified by the market structure of the technology producers and of the firms deploying innovation.

Figure 19: US technology adoption rates, years from consumer availability until 75% penetration



Source: Adapted by CL from deGusta (2012).

Figure 20: Average time from first adoption to 30% penetration, by market structure



Source: Adapted by CL from Shelanski (2000), Figure 10.

A.101 While there is substantial variation in deployment times for different technologies under a given market structure – from four to fourteen years under monopoly, four to twelve years under duopoly/triopoly, and two to seven years under competition – average deployment times speed up as markets become more competitive.

Impact on the economy

A.102 Mobile telephony has improved business communication and productivity across the economy and has led to greater economic activity. A series of studies, summarised in Table 9, have found a link between mobile penetration and economic growth. These studies, based on different samples across various countries, find that a 10% increase in mobile phone penetration of 10% has an impact of between 0.01% and 0.8% of GDP.[59] Studies have also found an increase in mobile telephony to drive increases in investment[60], as well as in labour productivity.[61] In particular, the impact of a 10% increase in 3G services alone is associated with an increase in GDP per capita growth rate of 0.15 percentage points.[62]

A.103 Several studies also find that the impact of mobile telephony on GDP can be up to twice as much in developing countries as in developed countries.[63] Especially in developing economies, mobile phone technology promotes economic growth by helping overcome constraints imposed by a less developed financial services sector.[64]

59 Sridhar and Sridhar (2004), Table 10; Waverman et al (2005), Table 6; Lee et al (2009), Table 3;

60 Paleologos and Polemis (2013), pages 4-5.
61 Bertschek and Niebel (2015), Table 5.2.
62 Deloitte (2012), page 5.
63 Sridhar and Sridhar (2004), Table 10.
64 Andrianaivo and Kpodar (2013), pages 22-23; Beck et al (2016), page 1.

Table 9: Summary of studies linking mobile telephone access and economic growth

Study	Data/sample used	Key findings
Impact on GDP or GDP per capita		
GSMA (2016)	Global, 2015	Mobile telephony and associated industries generated 4.2% of global GDP; directly employed 17 million jobs and contributed $430 billion through taxes in 2015.
Qiang (2009)	120 countries, 1980-2006	10% increase in mobile penetration is associated with: • a 0.6 percentage point increase in GDP growth rates for high-income countries; and • 0.8 percentage point increase for low- and middle-income countries
Deloitte and GSMA (2012)	Global, 2008-2011	A 10% increase in mobile penetration increases average annual GDP per capita growth by 0.65 percentage points. A 10% increase in 3G penetration increases average annual GDP per capita growth by 0.15 percentage points
Sridhar and Sridhar (2004)	63 countries, 1990 and 2001	10% increase in mobile penetration is associated with a 0.01 percent increase in GDP per capita growth.
Waverman et al (2005)	92 countries, 1980-2003	10% increase in mobile penetration is associated with: • 0.6 percentage points increase in GDP per capita growth for low-income countries; and • 0.3 percentage points increase in GDP per capita for high-income countries.
Lee et al (2009)	43 Sub-Saharan African countries, 2000-2006	10% increase in mobile penetration increases GDP per capita growth by 0.1 percentage points.
Gruber et al (2011)	Global, 1990-2007	Mobile telecommunications contributes 0.2% to annual GDP growth in high-income countries and 0.11% in low-income countries
Impact on labour productivity		
Bertschek and Niebel (2015)	2143 German firms in 2014	1 percentage point increase in share of employees with mobile phones increases labour productivity by 0.9%.
Impact on investment in the wider economy		
Paleologos and Polemis (2013)	30 OECD countries between 1988 and 2010	Positive relationship between the level of investment in the wider economy and an increase in competition in the mobile market.

Source: Various sources.

Summary and conclusions

A.104 Over the last four decades, mobile telephony has evolved from a fragmented set of systems across the world offering voice services (1G) to a world-wide system providing high speed data and voice services (4G).

a. 1G established seamless mobile connectivity introducing mobile voice services.

b. 2G digital wireless technologies increased voice capacity delivering mobile to the masses.

c. 3G optimized mobile for data enabling mobile broadband services, and is evolving for faster and better connectivity.

d. 4G LTE delivers more capacity for faster and better mobile broadband experiences and is also expanding into new frontiers.

A.105 Table 10 provides a summary of the differences between the four standards.

Table 10: Four generations of mobile standards

Standards	Technology	SMS	Voice switching	Data switching	Data rates
1G	Analog	No	Circuit	Circuit	N/A
2G	Digital	Yes	Circuit	Circuit	< 0.5 Mbps
3G	Digital	Yes	Circuit	Packet	Upto 2Mbps
4G	Digital	Yes	Packet	Packet	Upto 1Gbps

Source: Various sources – see previous sections.

A.106 The process that leads to standardization in the mobile telecommunication industry has changed considerably over time. Where it was first a national process, it has gradually changed into a more global process, and the role of the government in the standardization process has faded away, as summarized in Table 11.

A.107 The role of the government now mainly consists of creating 'boundary' conditions, i.e. conditions that limit market participants' influence on the standard setting process, such as competition rules and granting licenses to operate.

A.108 Finally, the number of stakeholders involved in the standardization process has increased considerably from stand-alone development of the standard to a situation in which a multitude of companies work together to develop standards. At the same time, the prices of devices and of mobile telephony services – voice and data - have declined over time.

Table 11: Differences in standardization regimes

	Region	Government role	Industry role
2G			
	US	No role	Consortia/stand-alone
	Europe	Mandate	SDO
	Japan	Mandate	Stand-alone
3G			
	US	No role	SDO/consortia/forum
	Europe	Boundary conditions	SDO/forum
	Japan	Boundary conditions	SDO/forum
4G			
	US	No role	SDO/forum
	Europe	Boundary conditions	SDO/forum
	Japan	No role	SDO/forum

Notes: SDO indicate Standard Development Organisation.
Source: Greeven and van de Kaa (2016), Table 6.

Case Study: TV Standards

Introduction

B.1 This section describes the various phases of standard adoption in the television industry, exemplifying heavy state involvement in the choice of standards. Through four episodes, we look at the drivers behind standard-adoption and the resulting economic outcomes:

a. The colour standard war in the United States between RCA and CBS in the 1940-1950s;

b. Global fragmentation in analogue TV standards: PAL, SECAM and NTSC in the 1960s;

c. High Definition TV standards as an interim step in the transition from analogue to digital, with the experiences of Japan, Europe and the US in the 1980-1990s; and

d. Global fragmentation in digital TV standards: ATSC, DVB, ISDB, and DMB in the 2000s.

B.2 In the age of analogue TV, government-determined technical standards promoted the interests of their national manufacturers and (often state-owned) broadcasters. The effect on consumer welfare was especially severe until the 1980s, as politicized standard-setting policies were coupled with direct trade restrictions against higher quality and cheaper imports from Asia.[65] In particular, Japan entered the US and European markets first through exports, and then (when its exports were restricted) through foreign direct investment in local production facilities.[66] In Europe, Japan also had to wait for the expiry of European TV standard patents, which protected domestic manufacturers.[67]

B.3 Digital TV era continues to be characterized by politically-influenced regional standards. However, the resulting inefficiency and the economic harm is likely to be less, since digital TV technologies are highly modular: a digital TV standard contains technologies used in many other products. The broadcast standards therefore affect only a small part of the supply chain and other standards, some of them set globally through open participation, affect much of the technology in a TV set. For example, the audio/video compression standards MPEG-2 and MPEG-4 are as critical to mobile phones as they are to digital televisions. Therefore, despite incompatible broadcast standards, there is wider competition in TV manufacturing than in the past.

Key components of a TV system

B.4 The TV system requires a standard for picture and sound signal format. These signals can either be **analogue** (stored in the varying amplitude and frequency of electromagnetic waves) or **digital** (stored as a sequence of numbers and carried as discrete pulses, where digits are represented by changes in voltage or light level) (Goleniewski 2001).

B.5 For either signal type, a television system has three components:

a. programming in the format by broadcasters;

  i. Capturing the picture and converting it to a signal line by line, along with audio,

b. transmission of the signal by networks, through four alternative means;

  i. via terrestrial (air) transmission over electromagnetic waves;

  ii. via cable networks that travel underground directly into households;

  iii. via satellites where the signal is projected to satellites and then back to satellite dishes; or

  iv. via wireless networks;

c. reception and display of the signal; where the devices can be:

  i. fixed, such as TV sets or set-top boxes; or

  ii. mobile, such as smartphones and tablets.

B.6 A TV standard has to be adopted by each layer of the TV ecosystem: broadcasters, networks and device manufacturers. Figure 21 below depicts the layers of the modern television ecosystem. Many of these options were not available in the first days of the television, where the only format was an analogue signal, via terrestrial transmission, into TV sets, for the purposes of linear viewing (at the time it was being transmitted, without the capabilities of recording and watching later, or without choosing among "video-on-demand".)

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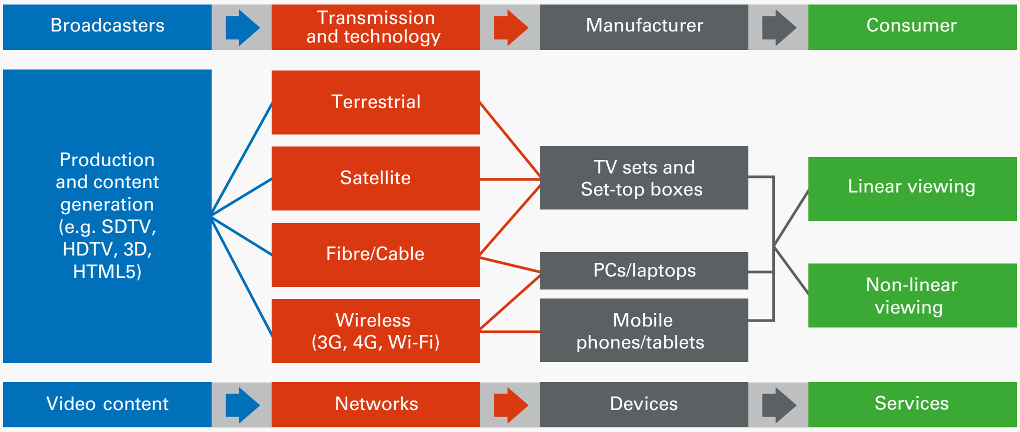
65 See Baldwin and Green (1988, p.209) for a discussion on US restrictions against Asian colour TV exports. In 1977, the US government used an "orderly marketing agreement" (OMA) to limit Japan's exports to not exceed 70% of its exports in 1976. Within two years, Japan's share of US colour TV market fell by eight percentage points. However, this share was captured by Japanese joint-ventures or plants in Taiwan and Korea, instead of domestic American producers. This forced the US to also negotiate OMAs with them (and later with Mexico and Singapore) in 1979. These restrictions led to an increase in Japanese foreign direct investment in the US, because imports of subassemblies were not restricted.

66 "It is demonstrated that Japanese foreign direct investment was basically a defensive response to trade barriers erected in these markets to relocate Japanese plant from Japan and other Asian locations" (Burton and Saelens 1987, p.285).

67 See paragraph B.44 and Angulo et al. (2011).

Figure 21: TV ecosystem



Source: Adapted by CL from DigiTAG (2014), Figure 5.

B.7 The first case study below discusses how incompatibility between layers hampers adoption of standards, even when they are technologically superior.

The colour war: RCA v. CBS in the US

Overview

B.8 In the 1940s, Radio Corporation of America ("RCA") and Columbia Broadcasting System ("CBS") competed to establish their colour TV system as the new standard in the US. This case is a leading example of how government agency-selected standards can go against market dynamics and may need to be reversed to adapt to market needs.

B.9 As we discuss in Section 3, governments often directly pick standards in the ICT sector in order to allow for faster technology adoption and development of network externalities. Left to market dynamics, the standard selection process may take longer. This would delay wider adoption and lock consumers into incompatible products (Angulo et al. 2011). However, government selection of standards cannot ignore customer preferences completely.

B.10 In 1950, the Federal Communications Commission ("FCC") wanted to introduce colour TV technology to the US market as soon as possible, and adopted the technologically superior CBS standard. However, the FCC failed to consider compatibility with consumers' existing TV sets and the market reality. Because the RCA system was backward compatible with the incumbent monochrome standard and because RCA was a leading manufacturer of TV sets, the RCA system was more quickly adopted by the market. In 1953, FCC had to replace the CBS standard with the backward-compatible RCA standard, which then became the National Television System Committee ("NTSC") standard (Shapiro and Varian 1999; Elen 2014).[68]

68 The facts and statistics regarding the US colour war in B.11-B.19 are based on Shapiro and Varian (1999) and Elen (2014).

CBS leading the standard war until 1950s

B.11 In the 1940s, the American broadcasting industry was dominated by two giants: RCA was a leading manufacturer and licensor of black and white TV sets, and CBS was a leading television network.

B.12 RCA and CBS proposed considerably different colour systems to replace the monochrome (black and white) standard. RCA aimed to utilise its installed base of monochrome television sets, so developed a compatible colour TV system. However, this backward compatibility complicated the RCA system considerably and delayed its development.

B.13 On the other hand, CBS based its colour television system on a new technology and presented it in 1940. Compared to the RCA system, the CBS system had better colour accuracy and lower studio and receiver costs. Although the CBS system was technically superior to the RCA system, it was not backward compatible with the installed monochrome sets. RCA's field rate was 60 fields per second whereas CBS' was 144, significantly reducing flicker and giving 24 complete colour images per second. Whereas monochrome television only used 6 MHz of bandwidth for transmission, the CBS system needed 16 MHz for its higher quality signal. This ensured enhanced television signals, but also meant that CBS had to use Ultra High Frequency ("UHF") channels in the spectrum, while monochrome televisions could only display signals from Very High Frequency ("VHF"). Existing sets would not be able to display any pictures from CBS' colour broadcasts, and colour TV sets made for the CBS standard would not be able to show any pictures from black and white broadcasts.

B.14 Throughout the 1940s, the CBS system held the technological lead in the standards war. It was delivering bright and sparkling images and was ready for the test transmission of the FCC, an independent government agency regulating technical aspects of broadcasting and the use of the spectrum. The Second World War put the standardisation attempts on hold and gave RCA time to improve its colour TV system, and also build up its installed base of monochrome sets. From 1946 to 1949, the number of monochrome TV sets in the US increased from around 6,000 to over three million.

B.15 In 1950, the FCC adopted the superior CBS system as the colour TV standard in the US. However, RCA had already won the standards war in the market. RCA owned over 90% of TV manufacturing capacity and the installed base of nine million monochrome TV sets, which were not compatible with the CBS standard. RCA contested the FCC's decision in court and delayed the adoption of the CBS standard by another eight months. Within this period, RCA increased its installed base of monochrome TV sets to twelve million.

B.16 In contrast CBS did not have any production capacities to produce colour TV sets. Therefore, it bought the TV set manufacturer Hytron and rebranded it as CBS-Columbia. In September 1951, CBS-Columbia released its first and last model, which sold less than 200 units. CBS's colour TV set was considerably more expensive than RCA's monochrome TV sets and could not display the monochrome broadcast. Colour TV broadcasting was only about 12 hours per week.

B.17 The Korean War further delayed colour TV: The US government suspended the production of colour TV sets, because material needed for colour TV sets was crucial for war efforts. By June 1952, the RCA colour system was finally ready and it was backward compatible with the now 23 million monochrome TV sets in the US.

Adoption of the NTSC standard in the US

B.18 Accepting the importance of backward compatibility for the adoption of colour TV, FCC endorsed the RCA system in 1953, which became the National Television System Committee ("NTSC") standard. RCA, the sponsor of the proprietary NTSC standard and the owner of around 90% of the TV manufacturing capacity, became the sole producer of colour TV sets.

B.19 However, with the absence of competition, RCA did not rapidly introduce its NTSC-television sets. RCA, as the incumbent supplier of monochrome sets, had weak incentives to innovate and replace itself. This lack of competition left consumers with a backward technology for another decade.

- In 1954, only 5,000 NTSC-standard colour TV set units were sold, because (i) colour TV sets were considerably expensive than the monochrome TV sets; and (ii) colour TV broadcasting was limited, adding little value to buyers.
- In 1957, NBC and CBS affiliates updated their transmission capacity to broadcast colour TV rapidly, but broadcasting networks were slow to produce colour TV programs.
- In 1963, only 3% of TV households had colour TV sets.
- Until 1964, colour programming was limited to special events or sports. In 1964, regular colour broadcast began.
- In 1965, while NBC broadcasted 4000 hours in colour, CBS and ABC offered 800 hours and 600 hours of colour TV broadcasting, respectively.
- Finally, in 1968, NTSC colour television set sales exceeded monochrome television sales.

Global fragmentation in analogue colour TV standards: PAL, SECAM and NTSC

Introduction

B.20 Setting universal technical standards allows for interoperability of products, wider network effects, and faster advancement of the technology by contributions from a wider pool of scientists. It also means freer trade and access to the highest quality and cheapest products by all consumers around the world. However, countries sometimes instead seek to promote their nationally-developed standards, to attempt to protect their political and economic interests. Adoption of colour television transmission standards around the world in the 1950s and 1960s exemplified this policy.

a. From a nationalist point of view, developing their national television standard was seen as a symbol of technological capabilities and cultural capitalism among the major powers of the Cold War era (Fickers 2010).

b. From an economic point of view, accepting a universal standard based on another country's technology required forfeiting royalties from domestically held patent rights, and instead paying licensing fees to a different country (Crane 1979).

c. From a trade point of view, having a patented national standard allowed for protectionism through a nontariff trade barrier. Different product standards and the resulting incompatibility initially completely inhibited and later (after the invention of integrated circuits compatible with multiple standards) discouraged consumers from choosing foreign manufacturers' products.

B.21 Domestic manufacturers therefore enjoyed dominance over production of colour televisions in their market (Lee 1996; Crane 1979), providing standard-owners with incentives to enlarge the adoption geography of their standard to widen their export market (and the cultural and political influence area of their home governments).

B.22 The United States officially endorsed NTSC as its colour television transmission standard in 1953, which was later adopted by Japan and some Latin American countries. In order to resist American dominance in the Cold War world and re-assert the French national power and prestige, France promoted the SECAM standard and created an alliance with the Soviet Union on colour television technologies. This standard was adopted in many former French colonies in Africa, as well as the Soviet Union. In order to avoid paying the high SECAM license fees, Germany created the PAL standard, which was eventually adopted by most of Europe and the rest of the world (Angulo et al. 2011).

Development of European colour television transmission standards[69]

B.23 Following the United States' NTSC standard announcement in 1953, Europe increased its efforts to replace the monochrome television standards with colour standards. By 1956, inventor Henri de France developed an alternative system called *Séquentiel Couleur à Mémoire* ("SECAM"). It built upon the principal inventions of NTSC, but significantly improved the colour accuracy by addressing the phase shifting errors (Townsend 1963; Bernath and Kobelt 1964, as quoted in Fickers 2010).[70] Three French industry giants[71] formed the joint venture *Compagnie Générale de Télévision*, to improve and develop the SECAM standard as an industry alternative to NTSC.

B.24 Meanwhile, Walter Bruch of the Telefunken Company in Hanover, West Germany developed a system called *Phase Alternation by Line* ("PAL"), which was an NTSC-variant heavily inspired by SECAM. Furthermore, the United Kingdom and Netherlands were experimenting colour broadcasting using the NTSC standard, instead of developing their own standards (Wu et al. 2006).

B.25 These standards had about 95% of their technicalities in common, but all promised to improve upon NTSC through different colour subcarriers, or variations in the number of horizontal lines (Crane 1979). The United States' NTSC system came to be mocked as the "*Never Twice the Same Colour*" system due to its low colour stability, which became the primary target of SECAM advertisements. In a 1962 Time magazine, a spokesman for SECAM ridiculed NTSC as only enjoyable by "dedicated knob twiddlers" and bragged that the French alternative was "the only system that ensures true colour TV in the home with the minimum fuss and bother, because the SECAM colour is not only accurate it is *automatically* accurate" (as cited in Fickers 2010). Meanwhile, direct French government political involvement in the development of the SECAM standard was mocked as *"Supreme Effort Contre Amerique"*, and the development of PAL as a response from Germany as the *"Provocation Allemande"*.

International conferences to select a standard

B.26 Technical experts regularly convened at CCIR[72] conferences to agree on international telecommunications standards. These conferences were "tedious, technical, detailed, and cooperatively progressive" in their nature. As the British Post Office representative noted, "without unanimity on vital technical issues international telecommunication is inhibited, if not impracticable. Thus the conduct of these Study Groups has always been on the basis of discussion, (. . .) and eventual erosion of the areas of disagreement" (Meriman 1965, as cited in Fickers 2010).

B.27 However, the heavy involvement of government authorities in the CCIR colour television Study Group meetings, and the lack of real decision-making power of the technical experts created a political, controversial, and non-cooperative atmosphere and the conferences dissolved with two rival European standards.

B.28 Going into the 1965 Vienna meeting, the colour television standard was of utmost political importance in France and Germany. SECAM was the "symbol of French (and especially Gaullist) grandeur", and PAL was the "expression of German workmanship and technical quality". In contrast, the UK and Netherlands had been experimenting with the NTSC system, and UK technical experts were ordered to "press strongly for NTSC; oppose the adoption of PAL; strongly oppose the adoption of SECAM" (quoted in Fickers 2010).

B.29 Promoting SECAM had such an important role in establishing the independent French stance in the Cold War era that President de Gaulle nominated an Inter-Ministry Delegate for the promotion of SECAM in 1965. In order to achieve Europe-wide adoption in the upcoming CCIR conference, de Gaulle aimed to secure Soviet support, and signed a cooperation agreement with the USSR. According to this agreement, the USSR could develop SECAM further without paying royalty fees. In exchange, it guaranteed support at the CCIR meetings and adoption of the system in all Eastern-Bloc countries.

B.30 The 1965 CCIR meeting convened in 25 March-7 April 1965 to select the European standard among NTSC, SECAM, and PAL. Unlike earlier meetings of the CCIR Study Group, where the delegations were mainly comprised of technical experts, this time the French delegation also had diplomats and the newly appointed Minister. As Fickers (2010) puts it, "this unprecedented and overt politicisation of a CCIR experts meeting changed the tone of negotiations from technical and scientific debate to strategic and political bargaining".

B.31 The ongoing disputes in the 1965 meeting postponed the colour television standard selection to the June 1966 CCIR Plenary Conference in Oslo. However, the 1965 meeting succeeded in removing NTSC from the choices. The British delegation, initially determined to press for the NTSC standard, observed a unified and strong support for the PAL standard at the conference from Scandinavia, Switzerland, Austria, and Italy. The German delegation was then invited to London to demonstrate PAL to British Post Office engineers and the Television Advisory Committee. In light of the post-conference meetings and the briefings of the British delegation to the 1965 conference, Britain decided to abandon its support for NTSC and joined the PAL-supporters. Meanwhile, Netherlands also joined the supporters of PAL with Philips research laboratories.

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69 This section and next draw extensively on Fickers (2010), which presents a fascinating blow-by-blow account of the some of the political struggles that resulted in the bizarre spectacle of an alliance between France and the USSR against, among others, West Germany.

70 NTSC's colour instability was due to the phase errors in transmission. SECAM's invention was to carry two pieces of the colour information (hue and saturation) sequentially on alternate lines (Wu et al. 2006).

71 The members of the joint venture were the Radio Industrie, Saint-Gobain and Compagnie de Télégraphie sans Fil.

72 CCIR stands for International Radio Consultative Committee. It was created in 1927 at the International Radiotelegraph Conference in Washington "to study technical and operating questions related to radio communications and to issue recommendations on them", holding regular international meetings. In 1992, International Telegraph Union's (ITU) three main areas of activity were re-organized as telecommunication development, radiocommunications, and telecommunication standardization, and CCIR was renamed ITU Radiocommunications. See, <http://handle.itu.int/11.1004/020.2000/s.002>.

B.32 British adoption of PAL in itself exemplifies the degree of political and economic concerns in standard setting. After the British Television Advisory Committee had recommended considering the PAL system for adoption after the 1965 meetings, the BBC took almost six months discussing the feasibility. BBC representatives (who were also a part of the British delegation to the conference) argued that "non-technical considerations such as programme exchange with the United States and the potential for television equipment exports to NTSC countries", and other political considerations made NTSC more favourable. This view was not welcomed by the Foreign Office, where the British ambassador in Bonn, Sir Frank Roberts expressed his concern about missing "a very promising political opportunity of functional cooperation and alignment with what is now I suppose our major European partner", West Germany. In October 1965, Foreign Office intermediary D. Brown announced that "if [*the technicians*] are still unable to reach agreement among themselves surely the time must come when a decision has to be taken by a higher authority, in the light not only of technical advice but of political and economic considerations". With the growing pressure from the Foreign Office and the Television Advisory Committee, the British Postmaster General finally internally declared the adoption of PAL as the British colour television standard in November 1965.[73]

B.33 As PAL gained Britain and Netherlands to join its ranks before the CCIR conference in 1966, the Franco-Russian alliance progressed with SECAM development. When the French met with their Russian counterparties in their first *Commission Mixte* meeting in May 1965, the Russians demonstrated an alternative standard called NIR, named after the Soviet Committee for the Coordination of Science and Technology (KNIR). Despite Soviet efforts to convince the French that NIR was based on SECAM and hence did not violate their agreement, the French authorities were uncomfortable with the new system that was substantially different than SECAM.

B.34 Meanwhile, technical experts from other countries were excited about NIR, which replaced the frequency modulation of the colour signal in the SECAM system with quadrature amplitude modulation used in the NTSC and PAL systems. This was seen as an exciting compromise between the two standards that could achieve European-wide support before the 1966 conference. BBC experts were among the interested group, despite the British delegation's official support for PAL.

B.35 However, as the technical experts discussed NIR with each other, all parties came to understand that whichever standard technical experts may favour, the final decision of their national authorities will be based on political interests:

a. The Soviets agreed not to promote NIR as a separate system with pressure from their French counterparties in the second *Commission Mixte* meeting. The NIR system was allowed to stay but was renamed SECAM IV, and the official Franco-Soviet recommendation to CCIR was selected as SECAM III. However, the Soviets were promised that both sides would switch to supporting SECAM IV if there were widespread European support for it at the conference.

b. Meanwhile, BBC representatives were reminded by their fellow delegates that "it will clearly not help *[Britain]* to secure support for PAL if the BBC plays a prominent part in the development and demonstration of a rival system" (quoted in Fickers 2010).

B.36 The CCIR conference in June 1966 began with a questionnaire to understand which delegations supported each of the competing standards. There were two large factions supporting PAL and SECAM III, and a smaller group consisting of Belgium, Luxembourg, Portugal, and Tunisia supporting NIR/SECAM IV. In the Study Group meetings, the French delegation made the surprising announcement that it would abandon SECAM III in favour of NIR/SECAM IV, if all other delegations accepted it as the European standard and invested in research and development to increase its commercial viability. British and German delegations objected to the proposal on the grounds that this would delay colour television in their countries for another year, and thus must be a decision taken by their respective governments. In the end, the PAL versus SECAM debate became so politicized that the chairman wrote in his final report the common hope of many delegates that colour television standards would never be discussed in a CCIR meeting again (Stanesby 1966c, as cited in Fickers 2010). The conference dissolved without agreement on the European standard; with the Anglo-German camp accusing the SECAM side of politicizing the discussions against CCIR's code of conduct and the Franco-Soviet camp accusing PAL supporters of standing against the unity of Europe.

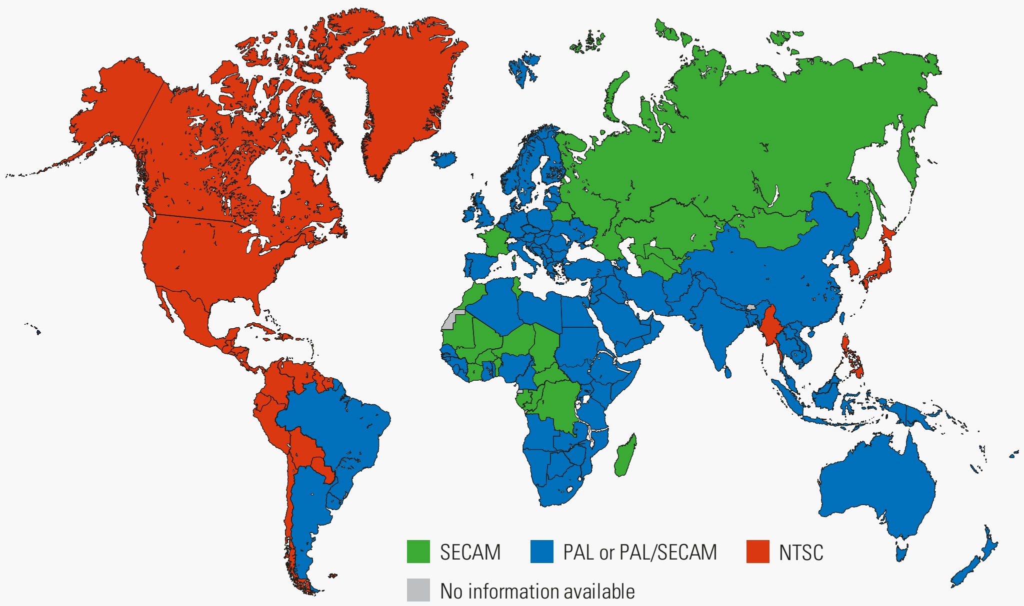
B.37 The disagreements at the CCIR meetings left the world with three competing television standards (Figure 22 shows the distribution today). The NTSC standard was adopted in the US as well as in Canada, Japan, and some Latin American countries politically and economically aligned with the US. SECAM standard was adopted in France and Belgium as well as in their former colonies, PAL adopted in Germany and most European countries.

Economic outcomes of the global fragmentation in colour television standards

B.38 Colour television standards were dominated by the interests of national manufacturing industries, broadcasters, and politicians. The manufacturers who developed the national standard pressed for the wider adoption of their standard in order either to reduce competition and monopolise production of sets for the standard or, at the least, gain revenue from licensing. Broadcasters promoted the acceptance of the national standard to enlarge their broadcasting area and revenues. European politicians' interests were aligned with those of their national standard-developer and national broadcaster. National manufacturers brought the royalty

73 Quotes are from Fickers (2010).

Figure 22: Analogue colour television standards around the world



Source: Adapted by CL from Angulo et al. (2011), Figure 1.

revenue to home country, and produced television sets or other related equipment at home creating employment and tax revenues. Moreover, a larger broadcast area for the nation meant larger political and cultural influence.

B.39 Regional standards that emerged after the CCIR conferences were also nontariff barriers to trade. Although PAL, SECAM, and NTSC had almost 95% of their technology in common (Crane 1979), manufacturers needed adjustments on TV sets to make them compatible with different standards. This decreased economies of scale and increased manufacturers' costs, harming their competitiveness in markets that adopted a different standard. Only from the mid-1970s onwards, TV manufacturers overcame this technical barrier with the implementation of integrated circuits. Decreasing component costs enabled TV manufacturers to produce TV sets compatible with several standards (Fridenson 1991).

B.40 In 1967, the average price of a television in France was 80% higher than in Germany. An internal note for the French Ministry of Information defended the necessity of the SECAM system to protect domestic manufacturers as follows: "The prices of production in Germany are lower by 25% to 30% than the prices of production for the same materials in France. Under these conditions, if Germany and France adopt the same system, the French industry will be in direct competition without contingent protection or customs with West German industry" (French Government Archives, as quoted in Fickers 2002).

B.41 The sponsors of PAL and SECAM heavily patented their standards as a protection from outside competition. Telefunken, the sponsor of PAL, refused to license its standard to foreign manufacturers, notably from Japan. This blocked Japanese entry to the PAL countries until 1970. Later, Telefunken granted only a restrictive license to exporters to the PAL countries and allowed them to manufacture TVs with small screens only. To grant a full license, Telefunken required that a manufacturer had to be located in a PAL country, which encouraged Japanese investments in European production facilities (Gaillard 2007). However, the competition in the PAL countries was already tough: new entrants could hardly break even (New Scientist 1981). Therefore, the Japanese manufacturers built up their presence in Europe only after Telefunken started licensing its technology and microelectronics to overcome incompatibility issues were invented (Gandal 2001). In France, Compagnie Générale de Télévision, the sponsor of SECAM, protected its home market via patents and also profited from import quotas imposed by France on Japan in the 1970s and 1980s (New York Times 1982).

B.42 PAL and SECAM also competed for export markets. The standard sponsors spent considerable resources to convince foreign governments to adopt their standards, so they could licence their standards to foreign producers and/or sell TV sets to foreign consumers. In France, TV set manufacturers, the French Broadcasting Corporation and Compagnie Générale de Télévision founded a new organisation, Intersecam, to coordinate the production of colour TV sets in France and to promote SECAM abroad, whereas the French government supported the efforts of Intersecam financially and politically (Fridenson 1991).

B.43 In May 1968, a patent agreement between Telefunken and Compagnie Générale de Télévision allowed German and French TV set manufacturers to receive licenses to produce and sell SECAM and PAL TV sets, respectively (Abramson 2002).

Table 12: Japanese manufacturers in the US colour television market

Year	Japanese market share (%)	Japanese firms manufacturing in the US (entry mode)
1970	16.0	
1971	16.4	
1972	14.3	Sony (greenfield investment)
1973	11.3	
1974	15.6	Matsushita (acquisition)
1975	27.1	
1976	47.3	Sanyo (acquisition)
1977	35.1	Toshiba (greenfield investment)
1978	31.5	Mitsubishi (greenfield investment)
1979	28.9	Hitachi (greenfield investment)
1980	34.7	Sharp (greenfield investment)
1981	43.5	

Source: Burton and Saelens (1987), Table 1.

B.44 In France, a wave of mergers resulted in the concentration of TV manufacturing under one company, Thomson-Brandt. Following the implementation of integrated circuits in the mid-1970s and the expiry of the PAL patents in the beginning of the 1980s, German manufacturers lost ground in their export markets (i.e. mainly Middle East and Africa). Many German manufacturers replaced their production with imports of Japanese TV sets on which they put their brands. Other German TV manufacturers were acquired by Thomson-Brandt or Philips (Fridenson 1991).

B.45 The United States resorted to import quotas to keep Japanese manufacturers out, as Japan had adopted the NTSC standard, eliminating that nontariff barrier. In response to the increase in the share of Japanese manufacturers in the US colour TV market from 16% in 1974 to 47% in 1976, the United States began imposing quotas on Japan in 1977 (Burton and Saelens 1987; Baldwin and Green 1988). In addition, Japan was under continuous threat of anti-dumping duties. Japan responded by relocating production plants and establishing joint ventures with other Asian companies in South Korea, Taiwan, and Singapore. The lost market share by Japanese companies as a result of the trade restrictions were immediately captured by these "other Asian" companies, which were in reality mainly Japanese. When the United States also negotiated Orderly Market Agreements to initiate quotas on these countries, many Japanese firms withdrew from East Asian countries and instead relocated to the USA, as summarized in Table 12.

B.46 The world's prevailing analogue standards are in some ways a legacy of the heavy role of the state in the economy in the post-war period. Promoting the interests of national manufacturers (sometimes state-owned) and national broadcasters (almost invariably state-owned), governments utilized regional standards as a protectionist measure, harming consumer welfare through higher prices. The resulting map of the analogue TV world is more based on political affiliations than any technical or commercial logic.

High Definition television standards and the switch to Digital Television

Introduction

B.47 High-definition television standards came as an interim step in the move from analogue standards to digital standards around the world. Technically, high definition television and digital television are separate concepts. Analogue versus digital relates to signal transmission, whereas high definition relates to picture quality. Just as standard definition television can exist in both analogue and digital transmission systems, analogue high definition systems could have existed standalone. However, high definition signals need to carry more information in the signal and they aim for higher quality image and audio. Since digital transmission can pack more information into a smaller bandwidth and offer lower interference-related errors (Angulo et al. 2011), exploration of analogue high-definition technologies naturally led to the development of digital television standards.

B.48 In this section, we summarize the development of analogue high-definition television, which eventually turned into the development of digital television. Japan was the pioneer in quality enhancement efforts in analogue, developing its commercially viable high-definition television standard in 1986. In order to avoid complete domination of their electronics sector by Japan, Europe and the US objected to the global adoption of this standard. Europe responded by developing an EU-funded analogue HD TV standard based on satellite transmission, which was rejected by the market as it was not profitable for satellite broadcasters. Therefore, the European television industry developed a more market-oriented update to the PAL standard, with lower HD quality. The US took longer to explore the next standard to replace NTSC, and decided on an all-digital high-definition standard. The US' jump to digital technologies forced Japan and the EU to also develop digital standards. Complete switch-off from analogue to digital television (including both standard and high-definition) occurred in a staggered way around the world in the late 2000s.

B.49 Digital TV compresses video and audio to smaller sizes than analogue TV and combines multiple signals into one signal for transmission. As a result, compared to analogue TV, digital TV uses the available bandwidth for transmission more efficiently, has a wider range of channels, provides better quality images and sound as well as lowers operating costs for broadcast and transmission. A digital TV system can transmit a wide range of picture and audio quality, from standard definition (which has about the same quality as analogue PAL and SECAM standards) to ultra-high definition.[74] Digital television standards are regional and incompatible, just as were the analogue standards. Although Europe eliminated the two camps and came together using one digital standard, the US-Japanese alliance in NTSC broke, and Latin America opted for a modified version of the Japanese standard with political considerations reminiscent of the analogue era in Europe.

High Definition television and the analogue enhancement efforts

Japan's HD technology

B.50 Japan was the first country to work on a future TV system which would provide consumers with a high quality TV experience, with efforts starting in 1964. The first technology it developed, "Hi-Vision", required a high transmission bandwidth that hindered adoption. In 1983, it developed the "MUSE" system, which compressed the required bandwidth from 30 MHz down to 8.1 MHz. This enabled cost-effective broadcasting of analogue HDTV channels via satellite transmission, which was again a technology developed by Japan's NHK (Wu et al. 2006).

B.51 In 1986, Japan presented the Hi-Vision/MUSE at the CCIR conference to be endorsed as the international standard for analogue high-definition television. At the time, Japanese manufacturers controlled a significant share of the television market in the US and Europe through their exports and local production facilities. To avoid further Japanese domination in their markets and to support domestic television industries, Europe and the US resisted this proposal (Lee 1996; Ala-Fossi 2016).

B.52 As broadcasting of the analogue HD TV system, Hi-Vision/MUSE, started in Japan in 1989, Europe and the US concentrated their efforts on developing rival technologies (Wu et al. 2006). Hi-Vision/MUSE's initial adoption in Japan was slow as well: although the transmission system was of much higher quality than NTSC, high-definition programming was scarce and the widescreen television sets that employed the standard were too expensive.

B.53 However, Japan's experience with HD analogue broadcasting was temporary, displaced by an all-digital standard as we shall describe later. The analogue Hi-Vision/MUSE standard was finally abandoned in 2007.

Europe's HD technology

B.54 The European Union and European manufacturing companies aimed to respond to the rise of Japan with a unified European standard, funded by the EU's *Eureka 95* project. The consortium of European manufacturers and public broadcasters focused their research on the "MAC" system, which was endorsed as the standard for direct-to-home broadcast satellite services in 1983. The new system focused on satellite transmission as in Japan, and the EU issued a MAC Directive in 1986 indicating that all direct-to-home broadcast satellite services using high-power satellites had to use MAC or HD-MAC (Wu et al. 2006).

B.55 The European Union Directive conflicted with the interests of satellite broadcasters, whose revenues depended on the number of channels transmitted. The increased picture quality in MAC systems did not contribute to additional profits, but limited the number of channels that could be transmitted due to the increased bandwidth requirement. Therefore, satellite broadcasters bypassed the MAC directive and used the prevalent PAL standard to save on costs. Consequently, most satellite receiver manufacturers ignored the MAC standards too. As a result, the HD-MAC standard failed to gain ground in the European TV industry (Wu et al. 2006).

B.56 In the meanwhile, European terrestrial networks and manufacturers had founded a strategy group in 1991 to compete with satellite and cable networks, since they could not transmit content from the HD-MAC system (Wu et al. 2006). This strategy group amended the PAL system to increase its picture quality, and presented "PALplus" in 1993. Despite its inferior quality to the HD-MAC standard, PALplus had more market success. In 1994, Nokia launched the first PALplus TV set, and German TV broadcasters began to adopt the PALplus system. In 1995, Samsung, a big Korean hardware manufacturer, joined the strategy group. In 1998, nine European countries were using the PALplus system.

United States and the switch to digital technologies

B.57 The US also invested heavily in high-definition technologies, to stop the decline in American competitiveness in technology manufacturing (Springer 1993, as quoted in Lee 1996). As in the earlier analogue technologies, there was a significant degree of government involvement. For instance, the US Labour Secretary Robert Reich wanted FCC to take into account the number of American jobs to be created in its selection of the HDTV standard (Lee 1996). Through the 1980s, the development of high definition technologies was also delayed due to FCC requirements that the new system had to be backward-compatible, which increased the bandwidth requirement.

74 There is a trade-off between image and sound quality and the number of channels. The higher the quality of broadcasting is, the lower is the number of channels, because a higher quality for image and sound requires a larger bandwidth for transmission (Brown and Picard 2005).

B.58 The FCC Advisory Committee on Advanced Television Service ("ACATS") received 23 proposals from 14 manufacturers for the new US standard to replace NTSC. Japan's analogue-based standard was among them, although it was later withdrawn because the FCC decided that the new standard had to be all-digital (Lee 1996; Angulo et al. 2011). Out of these, ACATS chose four in 1991. One was developed by *AT&T* and *Zenith Electronics*, one by *North American Phillips*, *Thomson Consumer Electronics*, and the *David Sarnoff Research Center*, and two were developed by *General Instruments and MIT*.

B.59 After testing these four technologies, ACATS recommended in 1993 that these companies should combine their efforts in a *"Grand Alliance"* to develop the next system. The *Grand Alliance* developed a new all-digital high definition system, while the industry group *Advanced Television Systems Committee* ("ATSC") defined the standard definition technologies to be added on. Together, these efforts created the United States digital television system "ATSC", for both standard and high definition.

B.60 The ATSC system focused on increasing the display quality of NTSC; however, it supports many different image sizes in standard definition as well. The reduced bandwidth requirement and the resulting efficiency allow more channels to be transmitted using less power. Therefore, the system is advantageous for reaching rural or peripheral areas with good coverage. On the other hand, ATSC did not create variant standards specific to terrestrial, cable, satellite, or mobile transmission, which created uncertainty among manufacturers over which image size to use, limiting network externalities.

B.61 The ATSC system was approved by the FCC in 1997, and is currently implemented in the NAFTA countries (US, Canada, Mexico), as well as in El Salvador, Dominican Republic, Honduras, and South Korea (Lee 1996, Angulo et al. 2011).

Digital television in Japan

B.62 In light of the all-digital television standards developed in the US, Japan also abandoned its analogue-based high definition standard in favour of an all-digital standard. This shift came with the pressure of major electronics manufacturers as well as the direct involvement of Ministry of Posts and Telecommunications. The Ministry founded *Association of Radio Industries and Business* ("ARIB") in 1995, which developed the Integrated Systems Digital Broadcasting ("ISDB") as the Japanese digital television standard. It also replaced the analogue-insistent NHK executives with those that supported digital (Angulo et al. 2011).

B.63 The ISDB standard has variants designed for each transmission method: ISDB-T for terrestrial, ISDB-C for cable, ISDB-S for satellite, and ISDB-H for handheld devices. An important aspect of the ISDB standard is that the bandwidth segment reserved for mobiles allow free reception of television signal. Other benefits include good indoor coverage of terrestrial transmission (i.e. with an antenna on the TV set) and increased number of channels due to the lower bandwidth requirement. The ISDB standard is currently implemented in Japan and (with important modifications to ISDB-T) in Argentina, Brazil, Chile, Costa Rica, Ecuador, Peru and Venezuela.

B.64 South American interest in the Japanese standard began with Brazil, and has grown in the rest of the continent due to commercial and political ties. From a technical point of view, Brazil was interested in a standard with good indoor coverage in terrestrial transmission, because more than half of the TV sets in Brazil used an indoor antenna (Angulo et al. 2011). Free reception by mobiles was another important factor. However, the real defining factors were based on commercial benefits: Japan allowed Brazil to make modifications to ISDB-T and granted partial exemption from royalty payments. Brazil developed "ISDB-Tb", which replaced the MPEG-2 audio/video compression standard in ISDB-T with MPEG-4. It also substituted the software with one developed by Brazilian industries. This made ISDB-Tb incompatible with the television set and codec[75] equipment manufactured in Japan, favouring local manufacturers and the electronics industry. In exchange, Brazil promised to promote ISDB-Tb in South American countries (Angulo et al. 2011).

B.65 Indeed, others such as Argentina, Chile, Venezuela (after testing all digital technologies except for the American ATSC), Ecuador, and Paraguay joined the ISDB-Tb standard. Some of these countries confirmed with technical reports that the ISDB standard offered superior quality in their geography, but most cited higher economic and political cooperation within the region as the reason behind their choice. Following Brazil's efforts, the Mercosur trade bloc now promotes and coordinates the development of ISDB-Tb in South America. It is also important to note that Japan promised financial support to all of these countries, either in the form of training activities, renovation or investment in their television industries, or exemption from royalties (Angulo et al. 2011).

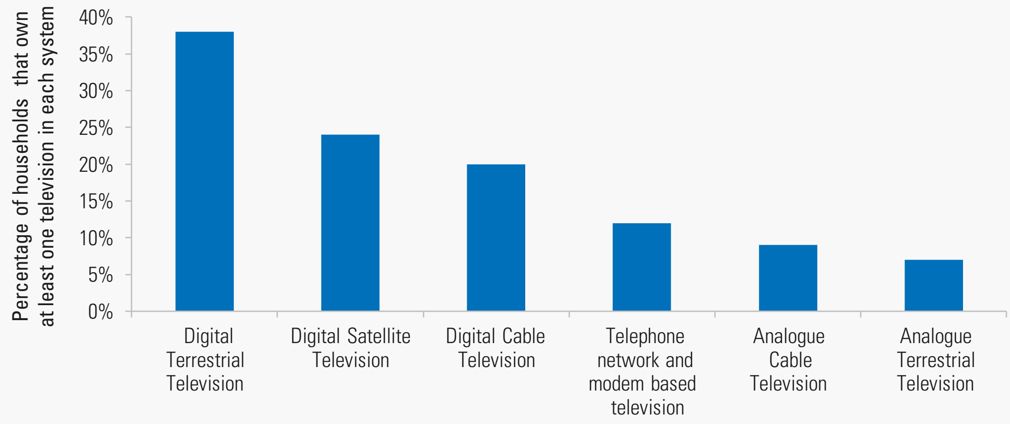
Digital television in Europe

B.66 Following the launch of digital TV systems in the US and in Japan, it became a perceived imperative among European politicians to develop a European digital TV standard to compete in world markets. The European Launching Group ("ELG") was founded in 1991 to discuss possible technology alternatives. This time, the focus of the TV industry was not solely on the increase in picture quality, but also on the proliferation of the number of TV channels. Therefore, satellite broadcasters were also interested in a digital TV standard, because it provided more channels.

B.67 In 1993, major European media interest groups (both public and private), consumer electronics manufacturers, network providers and representatives from national and European regulatory bodies joined the ELG and founded the DVB

75 "Codec" refers to coders-decoders that are needed in digital systems to convert the signal back to analogue (Goleniewski 2001).

Figure 23: Percentage of households in the EU using each television system in 2015



Notes: A household may have access to more than one system, so the percentages will not add to 100%.

Source: The European Union Open Data Portal. "Special Eurobarometer 438: E-Communications and the Digital Single Market." Available at <http://data.europa.eu/euodp/en/data/dataset/S2062_84_2_438_ENG>.

Project.[76] In contrast to the EU's centralized approach to develop the HD-MAC standard, the approach of the DVB Project in creating the DVB standards was consensus-based and relied on commercial considerations (Grimme 2002).

B.68 Similar to the Japanese ISDB standard, DVB has variants specific to each transmission method. The DVB Group developed the DVB-S system for satellite transmission, endorsed by the European Telecommunications Standards Institute ("ETSI") in 1994. The DVB-C system for cable transmission and the DVB-T system for terrestrial transmission became the European standards in 1994 and 1997, respectively.[77]

B.69 Unlike the ATSC which failed to agree on a patent pool, the DVB group formed a patent pool for all DVB standards (except for MPEG-2). The DVB standard is the most widely adopted standard around the world with all of Europe, Middle East, Central and Southeast Asia, most of Africa, and Oceania. In addition, Uruguay, Colombia, and Panama also implement the DVB standard[78]. The large geographic coverage of the DVB standard generates economies of scale for manufacturers (Angulo et al. 2011).

B.70 The transition to digital was completed through 2007-2012 in the EU countries. Figure 23 below reflects the percentage of households that own a television with each of the listed systems in the EU in 2015. Digital terrestrial television has the clear lead with 38%, followed by digital satellite in 24% and digital cable in 20% of the households.

B.71 Figure 24 shows the channel format for national channels via digital terrestrial transmission in selected European countries in 2013. Most content provided via digital terrestrial transmission is in standard definition (SD). The penetration rate of HD content varies across the European countries. While Germany and the Netherlands provide no HD content via digital terrestrial transmission, in France 28% of content via digital terrestrial transmission is in HD. It is expected that the penetration of HDTV sets to European households will increase the demand for content in HD, forcing national channels to provide more content in HD.

Digital television in China

B.72 Initially began using the European DVB-T standard in 2003, China later developed its national digital television standard, *Digital Multimedia Broadcasting Terrestrial/Handheld* ("DMB-T/H", later renamed "DTMB"). The DTMB standard has been jointly developed by Tsinghua University in Beijing and Jiaotong University in Shanghai, and endorsed as the national standard in 2006 (Burger et al. 2007).

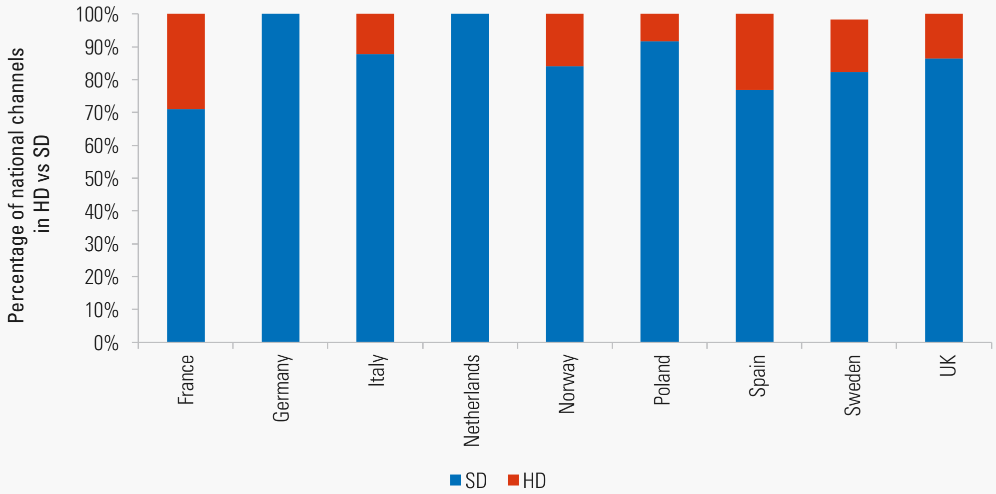
B.73 Compared to the ATSC (endorsed in 1996), and the DVB-T (endorsed in 1997), the Chinese DTMB came a decade later. This delay allowed Chinese developers to incorporate the best features from other standards to DTMB and design systems that respond to the latest consumer demand. For instance, DTMB offers fast and undisrupted reception in smartphones and rear-car entertainment systems, whereas these forms of viewing were not of high priority in 1996-1997. As a result, ATSC now needs retrofitting for mobile reception, whereas Chinese DTMB's reception was claimed not to drop even on a smartphone in a high-speed train. As a result, the DTMB standard can support mobile reception at higher speeds than the European DVB-T standard and transmit higher payloads than the American ATSC standard (Karamchedu 2009).

76 Initially, the DVB Project had 80 members of European origin. As of 2017, the DVB Project is an alliance of 200 companies worldwide. For the list of the members, see <https://www.dvb.org/members/list>.

77 See <https://www.dvb.org/about/history>.

78 Unlike other South American countries which based their choice on increased political and economic cooperation within the region, these three countries do not have cooperation agreements with each other. Instead, their choice was based on the promise of financial support and investment from Europe, and the ease of transition from the European PAL standard to the European DVB (Angulo et al. 2011).

Figure 24: Percentage of High Definition and Standard Definition national channels via digital terrestrial transmission in selected European countries, 2013



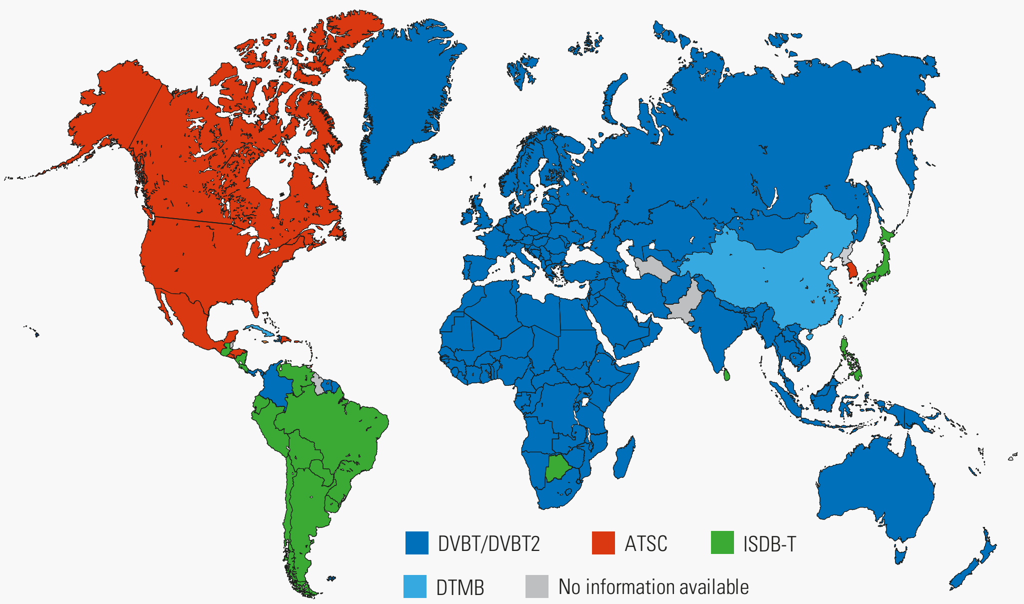
Source: Adapted by CL from DigiTAG (2014), Figure 6.

B.74 China is one of the largest TV markets in the world. It has around 427 million TV households, and 79% of them received digital signals by the end of 2015. China forecasts that digital signals will reach to 89% of TV households by the end of 2016 and to 100% of them by 2018 (Research and Markets 2016). In addition to China, Hong Kong, and Macau the DTMB standard is deployed in Cuba.

Comparison of digital television standards

B.75 Figure 25 presents a world map of digital television standards. Contrasted with the analogue era; there is less fragmentation intra-region due to stronger trade agreements, but more fragmentation globally. NAFTA countries all adopted the American ATSC standard, but this time Japan, a pioneer developer of the digital technology, insisted on its own ISDB standard. This fragmented Latin America between the American ATSC, European DVB, and the Japanese ISDB. Meanwhile, Europe, which had been strictly divided into two analogue camps came together in the digital technologies thanks to the European Union. Lastly, China emerged as a new player in the television industry.

Figure 25: Digital television standards around the world



Source: Adapted from the DVB map available at <https://www.dvb.org/resources/public/images/site/dvb-t2_map.pdf>.

B.76 Competition is forcing all standards to continuously upgrade, which enables convergence in quality and service. Table 13 presents the technical specifications of digital TV standards. Although Japan, Europe and the US had approached to the development of new technologies and standard setting differently, the resulting three standards deploy similar technologies for video and audio encoding. They differ in the transmission technologies they use, resulting in different service capabilities and quality. Table 14 compares the three most widely adopted digital terrestrial TV standards from the service aspect.

Table 13: Digital TV standards worldwide - Specifications

Type	ISDB	DVB	ATSC	DTMB
Video	MPEG-2 video	MPEG-2 video	MPEG-2 video	MPEG-2 video
Audio	MPEG-2 audio (AAC)	MPEG-2 audio (AAC)	Dolby Digital's AC-3	MPEG-2 audio (AAC)
Transmission: Satellite	Single carrier 8-PSK/PSK	QPSK and 8PSK	Undefined	QPSK and 8PSK
Transmission: Cable	Single carrier 64QAM	Single carrier QAM	64-QAM	Single carrier QAM
Transmission: Terrestrial	Segmented OFDM: QAM/DQPSK with time interleave	QPSK, 16QAM and 64QAM	8VSB modulation	TDS-OFDM

Notes: Modulation schemes

OFDM: orthogonal frequency-division multiplexing; QAM: quadrature amplitude modulation;

PSK: phase-shift keying; DPSK: differential phase-shift keying; TDS: time domain synchronization.

Source: ISDB: http://www.dibeg.org/techp/feature/ANNEX-AA.pdf

DVB: https://www.dvb.org/resources/public/factsheets/dvb-t2_factsheet.pdf, https://www.dvb.org/resources/public/factsheets/DVB-C2_Factsheet.pdf, https://www.dvb.org/resources/public/factsheets/DVB-S2_Factsheet.pdf

ATSC: http://atsc.org/standard/a53-atsc-digital-television-standard/, http://atsc.org/wpcontent/uploads/2016/03/a_52-2015.pdf, http://atsc.org/wpcontent/uploads/2015/03/A72-Part-1-2015.pdf

DTMB: Liu, M., M. Crussière, J. F. Hélard, and O. P. Pasquero. 2008. "Analysis and performance comparison of DVB-T and DTMB systems for terrestrial digital TV". In 11th IEEE Singapore International Conference on Communication Systems: 1399-1404. IEEE.

Alencar, M. S. 2009. Digital television systems. Cambridge University Press. Figure1.15.

Table 14: Comparison of digital terrestrial TV standards

Item	ISDB-T	DVB-T	ATSC
HDTV / SDTV fixed reception	Yes	Yes	Yes
Data broadcasting	In service	Possible, but unpopular	Possible, but unpopular
Single frequency network	Yes	Yes	No
Mobile reception	Good for both HD and SD	Only SD mobile reception is possible	Trials
Handheld reception	Good	Possible, but another frequency is required	Trials
Internet access	Good	Possible	Not good

Notes: HDTV: High definition TV; SDTV: standard definition TV.

Source: Table 1 in http://www.dibeg.org/techp/3comp/3comp.html

B.77 As shown in Table 13, the digital TV standards are collections of several modular standards for video and audio encoding as well as transmission systems. The modularity allows technology companies and/or expert groups to focus on a specific module which can be combined easily with other modules. A generic module can replace customised technologies and eliminate differences between standards adopted in different geographies. As an example, the MPEG-2 video encoding standard is deployed by all digital TV standards.

B.78 Another benefit of the modularity is that each module can be updated independently to incorporate recent developments in technology, making the update of the whole standard much easier.[79] Thanks to modularity, digital TV standards are in constant development. Experienced video quality is improving. The switch from SDTV to HDTV is in progress, and some channels have already stated to broadcast in the UHD format. Advances in video and audio encoding (such as the upgrade from MPEG-2 to MPEG-4) enable more efficient use of the available bandwidth.[80] For instance, the second generation European digital terrestrial standard in DVB-T2 introduces new modulation technologies which improve reception by fixed and mobile devices and increase transmission capacities, addressing the first generation DVB-T's shortcomings presented in Table 14.

The importance of modularity in preserving competition

B.79 Since the late 1990s, ICT markets have entered into cross-licensing arrangements called patent pools, partly to avoid the 'hold-up' problem that arises if there is more than one patent holder for a unified technology (including a standard).[81] Table 15 shows video and audio encoding standards used in the digital TV systems and the patent pool intermediaries managing patents involved in these standards. Initially, the digital TV systems deployed MPEG-2 and ACC encoding standards and then updated to the more advanced MPEG-4 standard. A patent pool is typically an *ad hoc* arrangement that may not contain all patents related to a standard. As an example, MPEG LA does not manage all patents related to the MPEG-2 video encoding standard, only a sub-group of them.

79 See Chapter 3 for the discussion on modular standards and benefits of modularity.

80 Compared to MPEG-2, MPEG-4 has a higher compression rate. In other words, it can maintain the same audio or video quality with a smaller file size. MPEG-4 is backward compatible with MPEG-2.

81 We discuss several forms of hold-up problem extensively in Chapters 3 and 4.

Table 15: Standards and patent pool intermediaries for video and audio encoding

Standard	Standard setting organisation	Patent pool intermediary	Product category
MPEG-2	ISO/IEC-MPEG	MPEG-LA	Video codec. Used in cable TV set-top boxes, DVD players and discs, video recorders, digital cameras, Blu-ray players and discs, digital television and high definition television.
AAC	ISO/IEC-MPEG	Via Licensing	Audio codec. MP3 technology.
MPEG-4 Visual	ISO/IEC-MPEG	MPEG-LA	Video codec. Used in digital media players, mobile phones, video cameras, internet services.
H.264 (MPEG-4 Part 10, or AVC)	ISO/IEC-MPEG (AVC); ITU-T (H.264)	MPEG-LA	Video codec. Used in Blue-ray and DVD players and discs, mobile broadcast video, portable game consoles, high-definition satellite TV. Used in HTML5.

Source: Barnett (2015) Table 2.

B.80 MPEG is a working group of the Joint ISO/IEC Technical Committee on Information Technology founded in 1988 to develop standards for video and audio encoding. The working group consists of around 200 companies and organisations from more than 20 countries. The MPEG-2 standard consists of several patents initially owned by various companies. In 1996, eight patent-holders agreed to pool their 27 essential patents in a patent pool managed by MPEG LA. In 1997, the Department of Justice exempted MPEG LA from antitrust law (Balto 2013).[82]

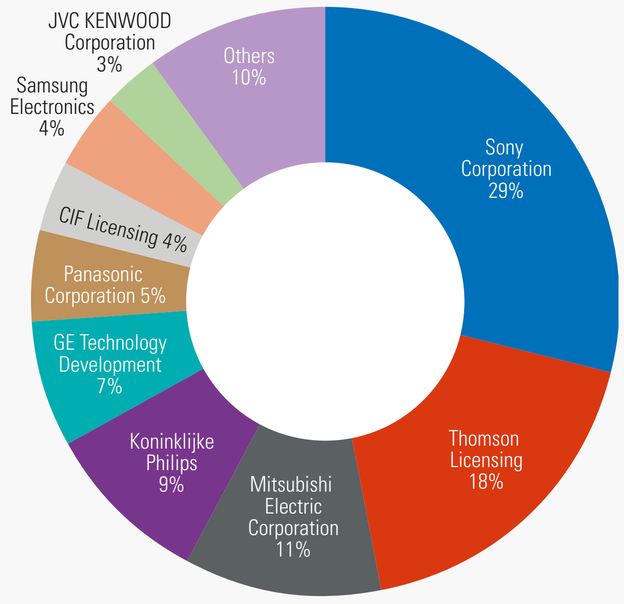
B.81 As of 2017, the MPEG-2 pool has 1112 licensees. The number of licensors in the MPEG-2 pool increased to 27, and the number of patents swelled to 1,082[83]. Figure 26 shows the distribution of the MPEG-2 patents between the licensors. Sony, Thomson and Mitsubishi are the three largest licensors.

B.82 The high degree of modularity in standards contributes to the competitive environment in manufacturing, despite the incompatibility of regional standards. The regional standards do not restrict TV manufacture to regional producers because the supply chain incorporates a great many technologies, most of them unaffected by broadcast standards. Figure 27 shows the strong competition among LCD TV manufacturers globally between 2008 and 2016.

82 Also see, <http://www.forbes.com/sites/bretswanson/2013/04/30/mpeg-la-shows-need-to-rebuild-ip-foundations/#65b2b7b85eac>.

83 For the list of licensees, see: <http://www.mpegla.com/main/programs/M2/Pages/Licensees.aspx>. For the list of licensors, see: <http://www.mpegla.com/ main/programs/M2/Pages/Licensors.aspx>.

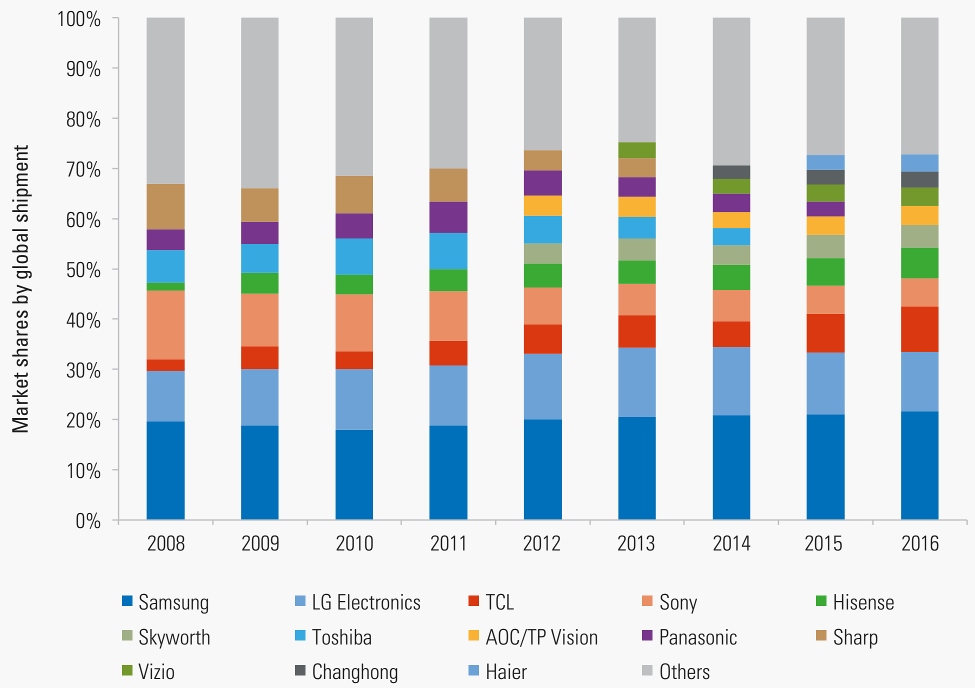
Figure 26: Share of MPEG-2 patents by licensor in the MPEG LA patent pool, 2017



Notes: Chart is based on total patent registrations data, which does not include patent family information. Therefore, registrations of one innovation in different countries would count as separate registrations. Others include 18 licensors with shares less than 3%.

Source: MPEG LA website. <http://www.mpegla.com/main/programs/M2/Documents/m2-att1.pdf>

Figure 27: Global market shares of LCD TV manufacturers, 2008-2016



Source: Adapted by CL from Statista chart <https://www.statista.com/statistics/267095/global-market-share-of-lcd-tv-manufacturers/>.

Summary and conclusions

B.83 Technical standards in the television industry have traditionally been influenced by governments' political considerations, which led to a fragmented landscape around the world. When the US developed the NTSC colour television standard, France immediately developed a national standard, SECAM. Although it improved upon NTSC's deficiencies, the motive for keeping a separate standard instead of proposing an upgrade of NTSC was establishing French technological independence. The rivalry within Europe between France and Germany resulted in two camps, with France, Russia, and former French colonies in Africa using SECAM, and the rest of Europe and the developing world using the German PAL standard. Meanwhile, Japan chose the American NTSC to enlarge export markets. Incompatibility between standards and the heavy patenting resulted in restricted global trade, with cheaper and higher quality Asian exports struggling to reach American and European markets.

B.84 The next phase of TV standard development began with high-definition analogue technologies, which Japan pioneered. The US and EU objected to the universal adoption of the Japanese high definition standard in the CCIR conferences, and instead developed their national technologies to strengthen national industries. As the market slowly adopted the Japanese and European high-definition technologies in analogue transmission, the US developed a *digital* television technology, compatible with both standard and high definition picture quality. This forced Japan and Europe to abandon analogue HD technologies in favour of digital HD/SD technologies. Hence, the global standards were once again fragmented between American ATSC, European DVB, Japanese ISDB. China also entered as a standard-promoter a decade after the cited standards, with DTMB.

B.85 Global adoption of digital television standards is heavily influenced by trade organisations and economic and political cooperation goals, rather than technical differences. Despite the incompatibility of regional standards, the high degree of modularity and common sub-standards between the different digital standards enables competition among manufacturers.

Case Study: PC Operating Systems

Introduction

C.1 In contrast to the open voluntary standards that are the main focus of this paper, PC operating systems ("O/S") have mostly been developed as proprietary standards, under the ultimate control of a single firm; although a few, based on Linux, go to the opposite extreme, as open source software. Market structure and the direction and pace of technological innovation have been influenced by this feature of the industry.

C.2 Operating systems also provide many examples of the classic benefits of standards. In particular, by creating a common platform they provide opportunities for producers of complementary products (hardware and software applications) to create compatible products.

C.3 This Annex explores the history of the development of O/S standards, both proprietary and open, and their impact on market structure and outcomes.

C.4 We begin with a brief introduction to the "technological stack" of PCs and the relationship between its layers, followed by a description of various proprietary and open source O/Ss. We then contrast how new versions of proprietary and open source O/Ss are developed. We conclude with an assessment of the impact of proprietary standards on competition, innovation and price levels.

Technological stack and O/S

C.5 A PC consists of different technological layers, called the "stack". Historically, these layers have been considered to be (from the bottom to the top):

a. hardware (such as microprocessor, graphic chips, camera, etc.);

b. O/S, such Windows, Linux or iOS;

c. application software, a term referring to all application programmes collectively.

C.6 However, the rapid expansion of the Internet from the mid-1990s onwards has added a new layer to the stack:

d. online services and cloud.

C.7 The layers of the stack are interconnected as below:

a. Hardware can take many forms but for most of the period considered here consisted of a PC, which itself is a bundle of many different components.

b. The O/S is the system software, i.e. a common platform for application software. It manages the hardware and application software resources and it intermediates between them.

c. The application software interfaces with the O/S, which in turn communicates with the hardware. This hierarchy ensures that the application software can run on different hardware.[84,85] However, the application software is O/S-specific. In other words, an application designed for a specific O/S runs only on that O/S and needs modifications to be able to run on another O/S.

d. Online services and cloud are O/S-independent. Online services refer to information and services provided over the Internet. Cloud uses a network of remote servers hosted on the Internet to store, manage and process data, eliminating limits set by a local server or a PC.

The development of operating systems for PCs

C.8 The PC industry has been shaped by standard wars between O/Ss, with Microsoft's O/Ss emerging as the market leaders. Vertically integrated O/Ss, such Apple's OS and IBM's OS/2, have a marginal role. Table 16 lists the main O/Ss and their sponsors in the PC industry. We describe each of these in turn in the following sections.

84 In the 1970s, the application software communicated directly with the hardware. Independent software vendors had to program in detail how an application program manipulates the hardware, manages memory, etc. That's why the application program had to be amended if there was a change in the hardware, making backward compatibility difficult.

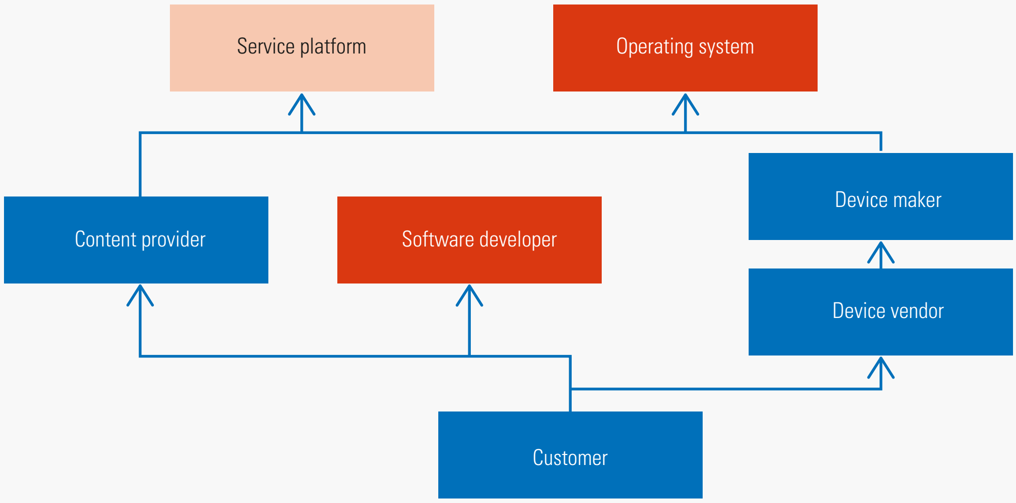
85 An application program can be designed to communicate directly with the hardware to maximize its performance. As an example, application programs for gaming consoles communicate directly with the hardware, because they require high performance, and gaming consoles, such as Xbox, have a standard hardware.

Table 16: Key PC O/Ss

O/S	Sponsor	First shipped	Type
MS-DOS, Windows	Microsoft	1981	Proprietary licensed
System OS, OS X	Apple	1984	Proprietary
Linux	-	1991	Open source

Source: Tanenbaum and Bos (2014).

Figure 28: Microsoft's role in the ecosystem



Notes: Microsoft launched its service platform, Windows Marketplace for Mobile, in 2009.
Source: Compass Lexecon.

Microsoft

C.9 Since the launch of the IBM PC in the early 1980s, Microsoft has had an O/S business: initially MS-DOS, then Windows. Microsoft also develops and markets business software applications, such as MS Office.

C.10 Microsoft has not in general integrated vertically through the stack, with its main business units being the operating system and software development (as shown in the red rectangles in Figure 28) with some involvement in the service platform (shown in a lighter shade of red in Figure 28).

From IBM PC to Wintel

C.11 The history of Microsoft's operating system begins with the decline of IBM in the PC industry.

C.12 In the early 1980s, the transition from 8-bit to 16-bit micro-computing disrupted the PC market. Building on its experience and reputation in other computer segments, IBM launched its 16-bit IBM PC (i.e. hardware) standard and replaced the established standard for 8-bit PCs called CP/M.

C.13 The IBM PC was an open hardware standard and relied on specialized players in the various layers of the stack, such as hardware components (e.g. microprocessors), O/Ss and software applications. Intel supplied IBM PC's microprocessor, whereas Microsoft provided its O/S (i.e. MS-DOS). Other complementary hardware components, such as disk drives, monitors and memory, were commoditized. Third-party developers provided software applications and strengthened the positive network externalities. To control the IBM PC standard, IBM relied on its proprietary Basic Input Output System ("BIOS") system, which manages the data flow between the computer's operating system and attached devices such as the hard disk, video adapter, keyboard, mouse and printer.

C.14 However, competing PC producers, such as Compaq, reverse-engineered IBM's BIOS and wrote alternative programs to circumvent IBM's intellectual property rights. As a result, IBM PC clones flooded the market. In 1983, around one million IBM PC clones were in use.[86]

C.15 In the mid-1980s, the transition from 16-bit to 32-bit micro-computing caused the next technological disruption in the PC market. In 1985, Intel launched its new 32-bit microprocessor, the Intel 80 386, which was considerably faster than the previous generation 16-bit microprocessor, the Intel 80 286. As the industry was waiting for IBM to introduce the new 386 machine, Compaq collaborated with Intel and launched the first 386 machine.[87] This move ended IBM's leadership in the PC industry.[88]

C.16 IBM's response was two pronged. IBM left its open hardware model and tried to take control of the PC industry with new IBM proprietary technology. IBM launched a new generation of IBM PC with its own proprietary hardware architecture, which was not backward compatible with the existing hardware. Due to the lack of backward compatibility, the new generation IBM PCs did not take off and failed to neutralize competition from other PC producers. The microprocessor started to define the new generation PC, and PC manufacturers started to label their 386 machines as "industry standard", instead of "IBM-compatible", marking the end of the IBM PC standard.

C.17 Another attempt by IBM to regain control of the PC industry was the release of a proprietary licensed O/S, called OS/2.

86 Gandal, N. (2002). Compatibility, standardization, and network effects: Some policy implications. Oxford Review of Economic Policy, 18(1), 80-91; p. 92.

87 http://web.archive.org/web/20090627055110/http://www.crn.com/crn/special/supplement/816/816p65_hof.jhtml

88 Bresnahan, T. F., & Greenstein, S. (1999). Technological competition and the structure of the computer industry. The Journal of Industrial Economics, 47(1), 1-40, p. 28.

Since 1985, IBM and Microsoft had been in collaboration on a new O/S but the partners had different plans. Microsoft wanted to build the Graphical User Interface ("GUI") of OS/2 on its Windows Application Program Interface ("API") for lower-end PCs only, whereas IBM wanted to develop a common GUI for all of its platforms, from mainframes to PCs. The partners had also different target markets. While IBM targeted high-end users with powerful PCs, Windows aimed for lower-end machines which constituted three quarters of the PC sales at that time. IBM refused Microsoft's offer to use the Windows API and, instead added to OS/2 features. However, the OS/2 brought little additional value to PC users and was a failure. IBM's share in global PC sales decreased to 14% in 1990.

C.18 In 1990, Microsoft launched Windows 3.0, which was a success in the low-end market as well as in the high-end market targeted by IBM. Consequently, in late 1990, IBM and Microsoft ended their partnership as they were in a standard war to supply O/S for Intel PCs.

C.19 In response to Window 3.0's success, in 1992, IBM released OS/2 2.0. OS/2 2.0 was the first O/S able to fully exploit 32-bit microprocessors by running application programs needing high processing power. Moreover, OS/2 2.0 already had a large application base: application programs written for DOS and Windows could run on it.

C.20 However, IBM's OS/2 2.0 could not gain ground against Windows and IBM lost the standard war against Microsoft. This was because IBM charged high prices for its developer tools and lacked the developer support Microsoft had. Instead of developing application programs for two competing O/Ss, developers chose to focus on Windows, with which they were already familiar. Moreover, IBM could not communicate its strategy with users and developers. Developers were confused as IBM was developing three other O/Ss simultaneously, in addition to OS/2, throughout the 1990s.

C.21 As a result, Intel and Microsoft became the new leaders in the PC industry, and the Wintel standard replaced the IBM PC standard. In 1996, IBM ceased the development of OS/2 and in 2004 sold its PC business to Lenovo from China. [89,90]

The four eras of Windows operating systems

C.22 Table 17 summarizes the development of Microsoft's O/S in four eras:

a. MS-DOS;

b. MS-DOS based Windows;

c. NT-based Windows; and

d. modern Windows.

89 Evans, D. S., Hagiu, A., & Schmalensee, R. (2008). Invisible engines: how software platforms drive innovation and transform industries. MIT press.; pp. 92-94.

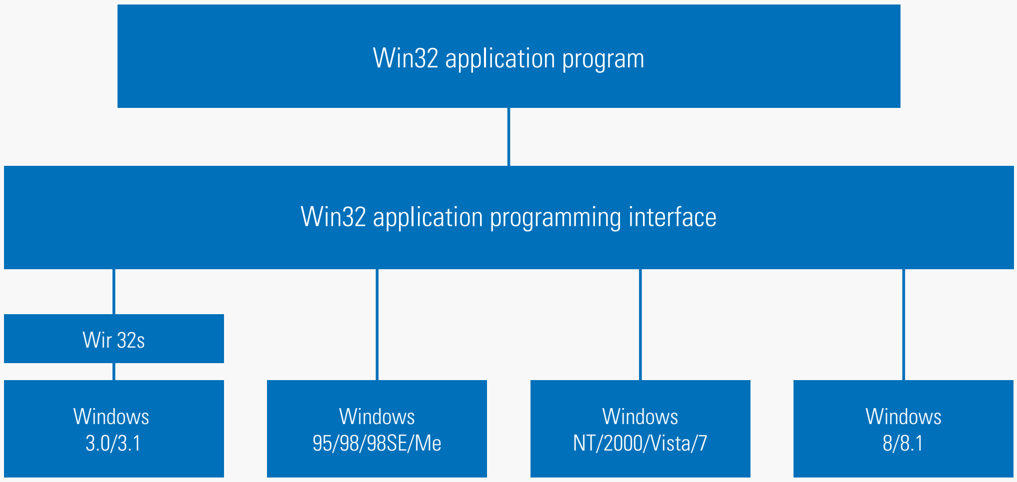
90 Last visited on 30 January 2017, https://www.cnet.com/uk/news/ibm-sells-pc-group-to-lenovo/

Table 17: Microsoft's major O/S versions

Year	MS-DOS	MS-DOS based Windows	NT-based Windows	Modern Windows	Notes
1981	1.0				Initial release for IBM PC
1983	2.0				Support for PC/XT
1984	3.0				Support for PC/AT
1990		3.0			Ten million copies in 2 years
1991	5.0				Added memory management
1992		3.1			Ran only on 286 and later
1993			NT 3.1		
1995	7.0	95			MS-DOS embedded in Win 95
1996			NT 4.0		
1998		98			
2000	8.0	Me	2000		Win Me was inferior to Win 98
2001			XP		Replaced Win 98
2006			Vista		Vista could not supplant XP
2009			7		Significantly improved upon Vista, MinWin approach
2012				8	First Modern version, launch of Microsoft Store
2013				8.1	Microsoft moved to rapid releases
2015				10	Launch of the Universal Windows Platform

Source: CL and Tanenbaum, A. S., & Bos, H. (2014), Figure 11-1 on p. 858.

Figure 29: Win32 API and backward compatibility



Source: Tanenbaum, A. S., & Bos, H. (2014). Modern operating systems. Prentice Hall Press; Figure 11-3 on p. 861.

C.23 As discussed in the preceding paragraphs, MS-DOS 1.0 was a modified version of an older operating system, CP/M, which was adapted to work on IBM PCs with the then-new '8086' processors. In 1981, it was shipped with the first IBM PC. Throughout the 1980s, MS-DOS evolved alongside hardware improvements of the IBM PC.

C.24 The 1990s was the era of MS-DOS-based Windows versions. They employed a graphical user interface ("GUI") built on top of MS-DOS. Microsoft's GUI was inspired by Xerox's PARC and Apple's Macintosh.

C.25 In the 2000s, NT-based[91] Windows versions replaced the MS-DOS-based Windows versions. In the early 1990s, MS-DOS was reaching the limits of its functional capabilities. Microsoft anticipated that the desktop, workstation and enterprise-server computing markets were converging, for which UNIX was the standard O/S. Moreover, new microprocessor architectures, such as RISC[92], were entering the market and challenging the Intel microprocessors for which MS-DOS and MS-DOS-based Windows were designed.[93] Consequently, Microsoft released NT-based Windows versions. The NT-based Windows versions were portable across different microprocessors, not only on Intel's. Most importantly, the NT-based Windows was backward compatible with MS-DOS-based Windows versions, because both of the versions used a common application program interface ("API"), Win 32.[94] Figure 29 illustrates the relationship between Win32 API and Windows versions in the last three decades.

C.26 The initial versions of the NT-based Windows had low adoption rates, because the number of 32-bit applications in the market was limited and backward compatibility with existing 16-bit applications was poor. Windows 95, released in 1995, addressed this backward compatibility problem and served as a bridge between MS-DOS-based and NT-based Windows versions. The era of MS-DOS-based Windows versions ended with Windows XP.

C.27 From MS-DOS 1.0 to Windows Vista, the size of the Windows versions increased rapidly. MS-DOS 1.0 consisted of about 4,000 lines of assembler code,[95] whereas Windows Vista had over 70 million lines. Microsoft keeps all APIs, applets, etc. of the previous Windows versions in the new versions to ensure backward compatibility between the Windows versions. This allows users to easily switch to a new Windows version.

Competitive dynamics in the 'Wintel' standard

C.28 Since the transition from MS-DOS to MS-DOS-based Windows versions in 1990, Microsoft had few competitors for its PC O/S and business software application (e.g. MS Office) products. Microsoft's trade secrets, patents and copyrights prevented competitors from developing compatible O/S alternatives. Microsoft's primary competitors on the IBM PC architecture were Linux and Open Office, which are open source and free. However, Linux did not have a significant application base and user base to create positive network externalities. Software packages developed to work for Windows did not work on Linux, and inefficient 'translation' programs were necessary to convert Windows and Office files to Linux and Open Office formats.[96,97]

91 "NT" initially expanded to "New Technology" but no longer carries any specific meaning.

92 Reduced instruction set computer (RISC) and Complex instruction set computer (CISC) are types of instruction set for processors. RISC processors have fewer instructions, and are used in modern processors.

93 In other words, MS-DOS and MS-DOS-based Windows did not work on PCs containing microprocessors different than Intel's.

94 API defines how different software components communicate with each other. Examples of APIs are Microsoft Windows API, POSIX, C++ Standard Template Library and Java.

95 Last visited on 13 January 2017, http://www.operating-system.org/betriebssystem/_english/bs-msdos.htm

96 Casadesus-Masanell, R., & Yoffie, D. B. (2007). Wintel: Cooperation and conflict. Management Science, 53(4), 584-598; p. 5.

97 For Linux see para C.60 ff.

Figure 30: Universal Windows Platform

Source: Microsoft. URL: https://msdn.microsoft.com/en-us/windows/uwp/get-started/universal-application-platform-guide

C.29 The technological stack of the PC industry created strong complementarities between the leaders of the Wintel standard, i.e. Microsoft and Intel. Realising these, they have cooperated and coordinated closely to release new products. Microsoft and Intel also collaborated to set standards related to the other layers of the stack. For example, in the early 1990s, Intel proposed the PCI bus to replace the existing slower ISA bus. Intel aimed to create an open and uniform standard for hardware producers which plug their hardware to the PCI bus. Microsoft supported Intel's efforts to convince hardware producers to accept the PCI bus as the new industry standard.[98]

C.30 However, despite the strong complementarity between Microsoft and Intel, their relationship has not been always smooth. The firms have different objectives and interests, leading to conflicts. While Intel derives profits from new computer sales only, Microsoft gains revenues from new computer sales and also from selling upgrades to the installed base. As a result, Windows releases a new O/S by every four to five years, while Intel's business model based on Moore's law requires release of new technologies by every 18-24 months. For instance, there were ten years between the release of Intel's 32-bit microprocessor (Intel 80386) and the release of Microsoft's 32-bit O/S (Windows 95).[99]

C.31 Worried about its dependence on Intel for microprocessors, in 1991 Microsoft sponsored the Advanced Computing Environment ("ACE") consortium. Consisting of 21 companies, the ACE consortium aimed to develop the RISC architecture for PC microprocessors.[100] The RISC architecture would replace Intel's CISC architecture and introduce new microprocessor manufacturers to compete directly with the incumbent Intel. The NT-based Windows versions were designed to work on both of the microprocessor architectures, RISC and CISC. Despite Microsoft's efforts, the ACE consortium failed to agree on a RISC architecture.[101]

Response to mobile devices

C.32 In the 2000s, the shift from PCs to mobile devices and the emergence of mobile computing and network-based services challenged Microsoft's O/S-based business model. To compete with Google and Apple, Microsoft has attempted to reinvent itself. Microsoft developed smartphone O/Ss and launched internet-related services and products (e.g. search, online advertising technologies and cloud services) to extend its business model from the O/S level up higher in the stack to online services and cloud.

C.33 In 2012, Microsoft launched Windows 8, which integrates the Windows O/S with Internet-related services and products. Microsoft built its new Windows version on the modular MinWin approach. According to the MinWin approach, the core consists of a small operating O/S which can be extended depending on the device (such as PC, smartphone or tablet) it was installed on. So, users have a common experience across different devices.[102] Together with Windows 8, Microsoft also launched Windows Store to distribute apps developed by Microsoft as well as third-party developers.

C.34 In 2015, Microsoft introduced Windows 10 and the Universal Windows Platform ("UWP"). The UWP is an application program platform common for any device running Windows 10, such as PC, tablet or smartphone, as described in Figure 30. Windows 10 will be the last version of Windows O/S, because Microsoft considers Windows not as an O/S anymore, but as a "service".[103] Today, Windows 10 is installed on more than 400 million devices in 192 countries.[104]

98 Casadesus-Masanell, R., & Yoffie, D. B. (2007). Wintel: Cooperation and conflict. Management Science, 53(4), 584-598; p. 7.

99 Casadesus-Masanell, R., & Yoffie, D. B. (2007). Wintel: Cooperation and conflict. Management Science, 53(4), 584-598; pp. 4-9.

100 RISC: Reduced instruction set computing; CISC: Complex instruction set computing.

101 Casadesus-Masanell, R., & Yoffie, D. B. (2007). Wintel: Cooperation and conflict. Management Science, 53(4), 584-598; p. 8.

102 Last visited on 13 January 2017, https://www.techopedia.com/definition/16270/minwin

103 Microsoft does not define "service" clearly. http://www.theverge.com/ 2015/5/7/8568473/windows-10-last-version-of-windows, last visited on 20 January 2016.

104 Last visited on 2 February 2017, https://news.microsoft.com/bythenumbers/ms-cloud

Table 18: Timeline of events for the TRON project

Year	Event
1981	IBM launched the PC and invited both Microsoft and Intel
1984	TRON project started
1988	First TRON chip developed
1989	The US threatened the Japanese government and industry with invoking 301 of the Omnibus Trade and Competitiveness Act
1990	TRON project collapsed

Source: Takahashi, T., & Namiki, F. (2003). Table 2.

Attempts at "de-Wintelization"

C.35 At various points, there have been attempts to challenge the Wintel standard: sponsored by government, key industry players or broader coalitions. Within the PC industry, all attempts have failed. However, as discussed previously, the increasing prevalence of smartphones and other mobile devices has recently challenged Microsoft's position as the market leader.

Japan's TRON project[105]

C.36 The TRON project, supported by the Japanese government and industry, aimed to develop an open O/S and microprocessor to rival the Wintel standard. Table 18 presents the timeline of events for the TRON project.

C.37 Founded in 1984, the TRON Association developed an open BTRON O/S and a TRON microprocessor, which had the potential to replace the Wintel standard first in Japan and then in the world market. BTRON had particularly strong advantages over the Wintel standard in Japan, because IBM-compatible PCs were unsuitable to process the Japanese language.

C.38 In 1989, 11 Japanese software developers founded the BTRON Group to promote the O/S. The BTRON Group's strategy was to develop a BTRON PC for educational purposes and to facilitate its adoption in Japanese schools with the support of the Japanese government. After the BTRON PC gained acceptance and a user base through its presence in Japanese schools, the BTRON Group would extend its efforts to the whole Japanese market and then to other world markets. Matsushita Electric developed the first BTRON PC for educational purposes and became a core member of the BTRON Group.

C.39 In response to Japanese attempts, the US government threatened the Japanese government and industry with invoking Section 301 of the Omnibus Trade and Competitiveness Act of 1988 against Japanese firms active in the US market. In order to protect their business interests in the US, members of the BTRON Group took a low profile and abandoned the project.

105 Takahashi, T., & Namiki, F. (2003). Three attempts at "de-Wintelization": Japan's TRON project, the US government's suits against Wintel, and the entry of Java and Linux. Research Policy, 32(9), 1589-1606; 1593-1596.

Linux

C.40 The open source Linux O/S has been an important element in attempts to introduce more variety into the PC and other computing O/S markets. We describe the history and development of Linux later in this annex (see para C.60 et seq).

Java

C.41 Microsoft has long been concerned not merely with direct challenges to its position in the O/S market but also to attempts to get around it. One direct challenge was Sun's Java.

C.42 Java is a general-purpose programming language developed by Sun Microsystems in 1995. Software applications written in Java are independent of O/S and computer architecture. They can run on any Java Virtual Machine installed on a computer, regardless of its hardware and the O/S installed on it.

C.43 In 1999, Sun Microsystems started to license Java free of charge, but retained its proprietary rights. In 2006, Sun Microsystems released the Java Virtual Machine as free and open source under the GNU General Public License ("GPL").[106]

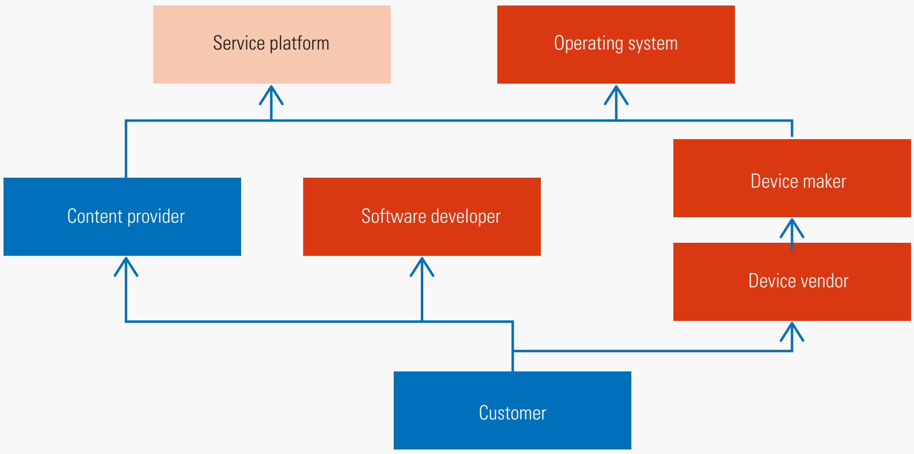
C.44 The ability to develop application software independent of the O/S would shift value away from the O/S level up higher in the stack to the application software level and thereby hurt Microsoft, the sponsor of the established standard in the PC industry. As a response, in 1997, Microsoft forked Java in its SDK to create fragmentation between different Java versions and undermine compatibility between them. Software packages developed using the forked Java version would work only on Windows O/S.[107] Sun Microsystems responded with a lawsuit, and Microsoft had to commit that its future software applications will pass Sun Microsystems' Java compatibility test.[108] Microsoft in effect gave up its forking efforts.

106 This means that third-party developers can copy, modify and use the JVM, and share their copies without any restrictions. However, all work based on the JVM core code has to be open source too. If requested, a third-party developer has to provide the source code of his/her version for free.

107 Last visited on 13 January 2017, http://www.javaworld.com/article/2077055/soa/what-does-sun-s-lawsuit-against-microsoft-mean-for-java-developers-.html

108 Last visited on 13 January 2017, http://www.javaworld.com/article/2074908/sun--microsoft-settle-java-lawsuit.html

Figure 31: Apple's role in the ecosystem



Notes: Apple launched its service platform (iTunes) with the third generation iPod in 2003.
Source: Compass Lexecon.

Antitrust cases

C.45 Microsoft's high share of shipments of PC O/S and its anticompetitive practices engaged the attention of the competition authorities from the US and the EU from the beginning of the 1990s. While the US Department of Justice was concerned with the tying of Internet Explorer ("IE") with Windows and the forking of Java, the European Commission ("EC") dealt with the tying of Windows Media Player ("WMP") with Windows and refusal to provide complete information to servers.

The US v Microsoft

C.46 The 'browser wars' that resulted in an antitrust investigation by the US Department of Justice (and the European Commission – but the issues were similar) had, at their root, a fear that a browser such as Netscape Navigator could create a platform for users to run application software that could sit atop any operating system. In effect, just as Microsoft itself 'commoditised' the hardware in a PC, by enabling application software to work directly with the O/S on any hardware, so Windows itself might be commoditised by the appearance of a new layer.

C.47 The issue central to the case was whether Microsoft was allowed to bundle its Internet Explorer (IE) web browser software with its Microsoft Windows operating system. Bundling them together was alleged to have been responsible for Microsoft's victory in the browser wars as every Windows user had a copy of Internet Explorer. It was further alleged that this restricted the market for competing web browsers (such as Netscape Navigator or Opera) that had to be downloaded over a modem or purchased in a store. Underlying these disputes were questions over whether Microsoft altered or manipulated its APIs to favour Internet Explorer over third party web browsers, Microsoft's conduct in forming restrictive licensing agreements with original equipment manufacturers (OEMs), and Microsoft's intent in its course of conduct.

C.48 Following extensive litigation involving various parties and an extended trial, the DoJ agreed to settle the case with Microsoft in 2001, nine years after the Federal Trade Commission's initial investigation into Microsoft's abuse of dominance in the PC O/S market. The proposed settlement required Microsoft to share its APIs with third-party companies and appoint a panel of three people who will have full access to Microsoft's systems, records, and source code for five years in order to ensure compliance.

The EU v Microsoft: Windows Media Player and servers

C.49 The European Commission brought a case against Microsoft for abuse of its dominant position in the market. It started as a complaint from Novell, a software company, over Microsoft's licensing practices in 1993, and eventually resulted in the EU ordering Microsoft to divulge certain information about its server products and release a version of Microsoft Windows without Windows Media Player.

C.50 In 1998, the EU focused its investigation of Microsoft's anti-competitive practices to examine of how streaming media technologies, such as the Windows Media Player, were integrated with Windows.

C.51 The EU reached a preliminary decision in the case in 2003 and ordered the company to offer both a version of Windows without Windows Media Player and the information necessary for competing networking software to interact fully with Windows desktops and servers. In March 2004, the EU ordered Microsoft to pay €497 million, the largest fine ever handed out by the EU at the time, in addition to the previous penalties, which included a requirement to to divulge the server information in 120 days and to produce a version of Windows without Windows Media Player in 90 days. Eventually, Microsoft had to pay an increased fine of €860 million for non-compliance with the Commission's order.

Apple

C.52 Apple is vertically integrated (as shown in Figure 31) and outsources the production of its PCs to device makers and sells the final devices through its Apple Store. Apple's O/S is only bundled with its PCs and is not licensed to other device makers. Apple also develops and markets business software applications for creative businesses (such as architecture and graphic design) to complement its O/S.

History

C.53 In the 1970s, Apple was the leader of the microcomputer (later called PC) segment, but in the 1980s, the IBM PC standard and later the Wintel standard replaced Apple.[109] Apple entered the PC segment with the launch of its vertically integrated Macintosh standard in 1984, but it could hold ground only in education and desktop publishing. Apple's share of PC shipments was only 7.4% in 1990 and decreased to 2.8% in 2000.

C.54 Apple and Microsoft differed starkly in their business models. Apple's vertically integrated ecosystem allowed it to tailor its O/S and hardware together and optimize the performance of its Macintosh platform. Apple did not license its proprietary O/S to other PC manufacturers. In contrast to Apple, Microsoft had a vertically disintegrated ecosystem and focused only on the O/S layer. Microsoft relied on outsiders for hardware, but it collaborated closely with them to optimize the performance of its O/S. Microsoft licensed its proprietary O/S to other PC manufacturers.

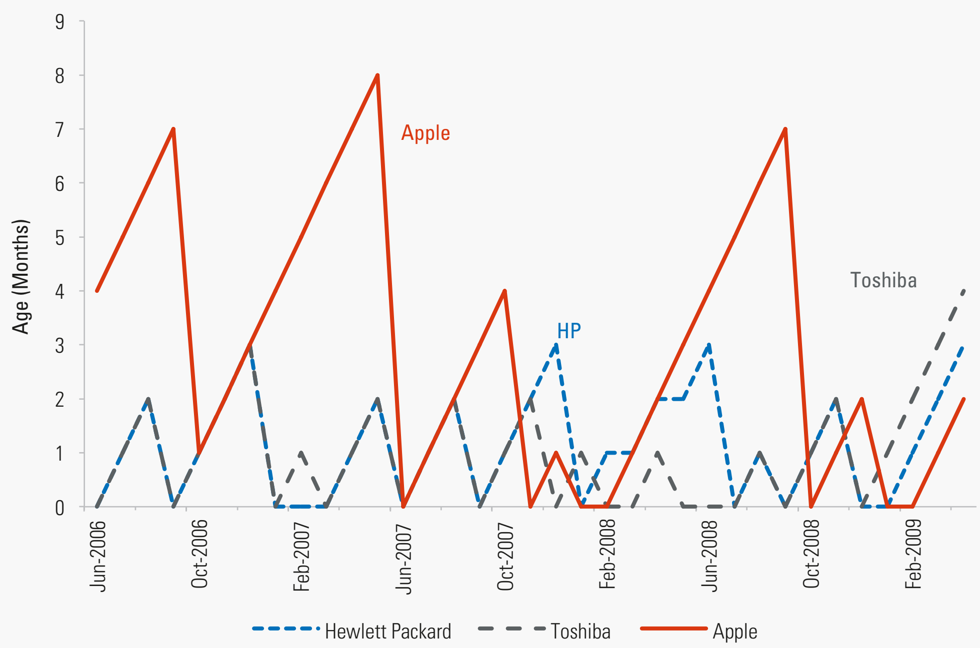
C.55 There is clear evidence that the more open systems lead to faster innovation. Copeland and Shapiro (2010) found that Apple introduced new chips less frequently even than individual rivals such as HP and Toshiba which used the Wintel platform. Figure 65 plots the age of the CPU after its launch in the latest version of Apple, Toshiba and HP PCs. The vertical axis shows the age of the CPU (i.e. months since the CPU's commercial launch). For example, in October 2006, Apple's PC had a CPU that was launched in September 2006. The September 2006 CPU was used until June 2007.

C.56 Figure 32 shows that the rate of product introductions was much faster for Wintel than for Apple. Toshiba and Hewlett Packard were twice as often the first to adopt a new CPU (12 and 14 months out of 35, respectively) as Apple (7 out of 35 months). Further, Hewlett Packard and Toshiba rarely kept a CPU beyond its three month anniversary, while on three occasions, Apple's newest CPU available was seven months old.

C.57 Furthermore, the same study found that Apple's prices did not decline significantly over the product cycle, presumably because it was not facing new, higher-performance competitors. Figure 33 shows that Apple's prices declined by less than 5%

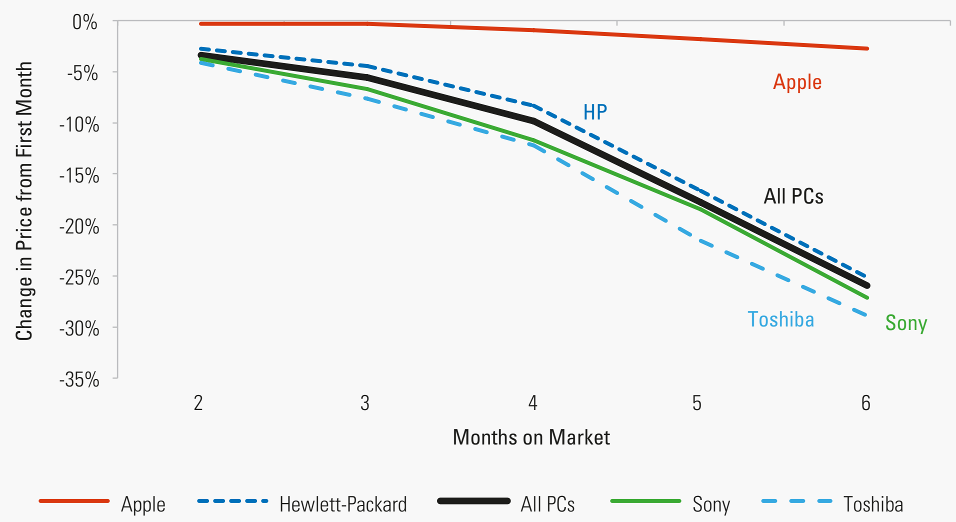
109 Wonglimpiyarat, J. (2012)

Figure 32: Adoption of Intel CPUs, June 2006-March 2009



Source: Adapted by CL from Copeland and Shapiro (2010), Figure 3.

Figure 33: Price Declines over Product Cycle



Source: Adapted by CL from Copeland and Shapiro (2010), Figure 4.

six months following the launch of the corresponding Apple PC whereas the price of PCs in general declined by 25% on average in the six months following its launch.

C.58 Despite having some strong supporters, the Macintosh system that included Apple's O/S never achieved more than a minority market share, usually less than 10%. The main factors for the Macintosh's failure to challenge the Wintel standard are:

a. Macintosh was not backward compatible with Apple II, the leader in the microcomputer segment in the 1970s and thus could not make use of its user base;

b. Macintosh's GUI was well ahead of IBM PC's, but it lagged behind in other key innovations, such as colour screen, expansion slots, hard disk, etc. Moreover, as an open hardware standard, the Wintel standard could incorporate new technologies easily, while Apple's bundled platform needed more time to make adjustments; and

c. Macintosh platform lacked positive network externalities. Targeting high-end users, Apple charged high prices for its Macintosh PCs and did not license its O/S to other PC manufacturers, while Microsoft set low prices and collaborated with PC manufacturers to pre-install its O/S.

As a result, Microsoft built its installed base aggressively leading to positive network externalities. Application developers preferred the Wintel standard over the Macintosh standard and provided the complementary application base. In the 1990s, over 80% of software titles launched for personal computers were only available on PCs.

Linux

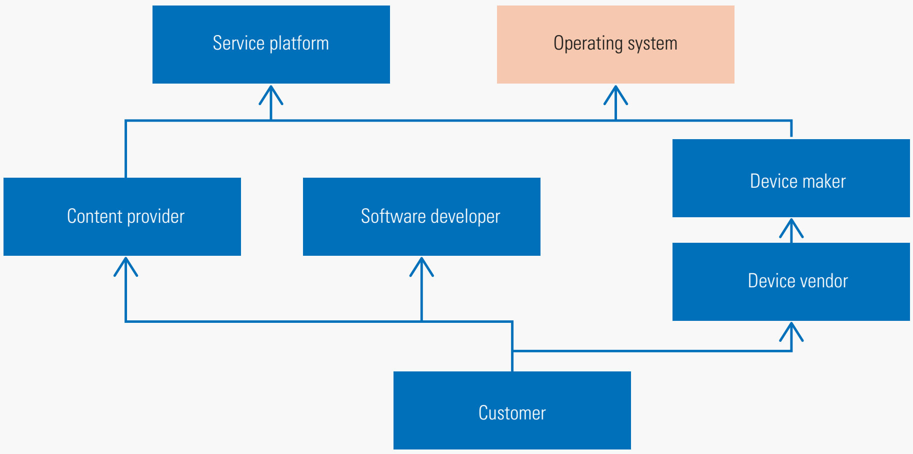
C.59 Linux is an open-source O/S copyrighted under GNU General Public License ("GPL"). This means that third-party developers can copy, modify and use Linux, and share their copies without any restrictions. However, all work based on the Linux kernel has to be open source too. If requested, a third-party developer has to provide the source code of his/her version for free.[110] Figure 34 shows the decentralised ecosystem of Linux. The O/S rectangle is lightly shaded, because Linux is an open source O/S.

C.60 In contrast to a proprietary O/S, such as Windows, Linux was developed as a result of the collaboration of several stakeholders. Free Software Foundation ("FSF"), a non-profit organisation founded in 1985, promotes the free software movement and supports the GNU project. This project provides the set of packages and tools to develop Linux for free. Using these tools, many developers have collaborated over the Internet and contributed to the development of Linux.

C.61 As a result of the open source policy, there are several commercial and non-commercial Linux distributions in the market. In addition to the basic Linux O/S, a Linux distribution contains utilities for management and system installation as well as ready-to-install software packages for web browsing, text editing, games, etc. The vast number of Linux distributions has not lead to fragmentation in the Linux world. A software package written for a Linux distribution would work on another Linux distribution.[111]

110 Tanenbaum, A. S., & Bos, H. (2014).
111 Silberschatz et al (1998).

Figure 34: Linux's role in the ecosystem



Source: Compass Lexecon.

History

C.62 A Finnish computer science student, Linus Torvalds, developed Linux as a variant of UNIX in 1991. Because Linux is open source and free, several developers have collaborated and contributed to the development of Linux over the Internet and helped it to become a full-featured O/S which runs on all platforms. Today, Linux is an alternative to other UNIX variants and established O/Ss in the market.[112]

C.63 UNIX had been developed by the Bell Labs (a subsidiary of AT&T) in the 1970s. Because AT&T was a regulated monopoly at that time, it licensed UNIX to academic and commercial institutions for small fees. By the end of 1980s, this led to a fragmented UNIX world with a large number of variants, such as System V of AT&T, BSD of University of California, Berkeley, Xenix of Microsoft, AIX from IBM and Solaris of Sun Microsystems.

C.64 The fragmentation in UNIX made it harder for third-party developers to write a software package which would run on any UNIX variant.[113] Initial standardisation attempts by individual institutions, such as AT&T, failed, because competing institutions did not accept these. After long discussions, the IEEE Standards Board, a neutral body, proposed the 1003.1 standard, which was the intersection of the two most widely used UNIX variants, System V and BSD, including only features common to both UNIX variants. As a result, a software package written in compliance with the 1003.1 standard would work on both of the UNIX variants.[114]

C.65 A lawsuit between AT&T and Berkeley helped Linux to replace the two most widely used UNIX variants, System V and BSD. In 1992, Berkeley released a final version of its BSD as an open source. As a response, in 1993, the AT&T subsidiary controlling UNIX sued Berkeley and other companies developing BSD packages and providing support. The lawsuit prevented the sale of the free and established BSD in the market long enough and gave room to the young Linux to establish itself. The case was later settled.[115]

Adoption of Linux: advantages and barriers

C.66 Over the last two decades, fewer than 4% of PC users have adopted Linux[116] although Linux has relative advantages compared to proprietary O/Ss, such as Windows. These are:

a. Linux has low total cost of ownership ("TCO"), because its distributions are delivered for free (or for low fees) and it is mostly immune to crashes and bugs. Members of the large Linux community can check and fix the O/S's open source code, while users do not have access to the code of a proprietary O/S;[117]

b. Linux is more secure, because there are no common viruses for Linux and the large Linux community can respond to security bugs of the O/S quickly;[118] and

c. Linux can run on old hardware, even on 486 processors, while Windows requires advanced microprocessors and large memory for its new releases.[119]

C.67 While Linux's market share among PC users is quite low, the advantages listed above are more pertinent to sophisticated users such as enterprise application developers. In the four

112 Stallings, W., & Paul, G. K. (1998).

113 A software package written for MS-DOS would run on any MS-DOS system. As a result, the application base for MS-DOS and early versions of Windows increased rapidly.

114 Tanenbaum, A. S., & Bos, H. (2014).

115 Tanenbaum, A. S., & Bos, H. (2014).

116 Because Linux is not distributed by retail sale, the adaptation figures are calculated using proxies such as web searches. These figures are widely criticised, because web figures tend to overweight O/S figures from the West, which uses mostly Windows as O/S.

117 Coverity Open Source report found out that open source software code has fewer defects per thousand lines of than proprietary software code. Last visited on 1 February 2017, <http://www.pcworld.com/article/2038244/linux-code-is-the-benchmark-of-quality-study-concludes.html>

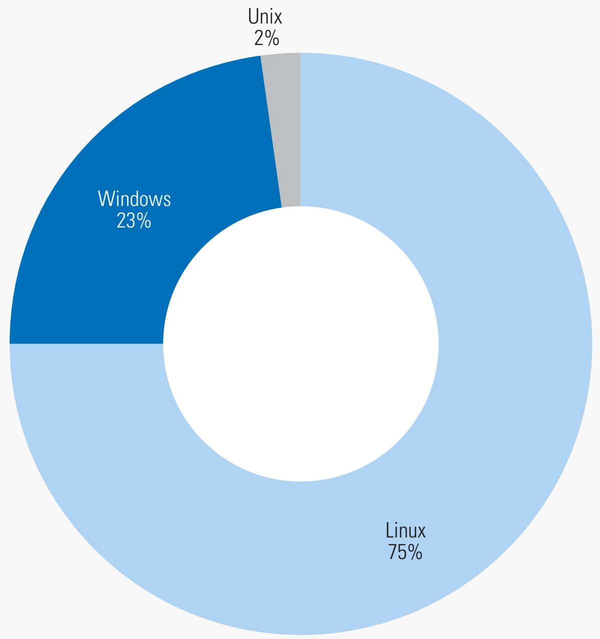
118 Last visited on 1 February 2017, <http://www.pcworld.com/article/202452/why_linux_is_ more_secure_ than_windows.html>

119 Kshetri, N. (2005). Diffusion pattern of Linux: An assessment on major technology dimensions. First Monday, 10(8). <http://pear.accc.uic.edu/ojs/index.php/fm/article/view/1263/1183

years from 2011 to 2015. Linux application deployments have risen from 65 percent to 79 percent, while Windows deployment has fallen from 45 percent to 36 percent.

C.68 Linux also seems to be the preferred platform for cloud computing. In 2014, a Linux survey found 75% of the total sample preferred Linux to other platforms (Figure 35) .

Figure 35: Primary Cloud Platform, 2014



Source: The Linux Foundation (2014)

C.69 However, there are also barriers for Linux's adoption:

a. equipment makers deliver PCs mostly with Windows pre-installed, while users have to install a Linux distribution themselves;

b. there is a large variety of Linux distributions. These may be incompatible with each other and may not offer backward compatibility with the application base;[120]

c. familiarity with and investment in Windows products as well as compatibility issues with trade partners (if they use Windows products) may increase users' switching cost;

d. in contrast to well-established proprietary O/Ss, Linux requires medium or expert technical expertise to decipher developer forums for help or to tailor the O/S for consumer needs;

e. there are considerably fewer software applications developed for Linux than for Windows, and application packages having the same purpose (such as OpenOffice for Linux and MS Office for Windows) do not have the same functionality; and

f. some hardware and devices may not have adequate drivers for Linux or their drivers may be available later than the ones for Windows.[121]

The points (e) and (f) refer to complementarity with the other layers of the stack such as application software and hardware, respectively.

Effects of proprietary control of the operating system

C.70 We have already noted (at C.52 *et seq.*) that Apple's closed system seemed to result in slower introduction of new hardware than the Windows O/S, which is open to competing suppliers of hardware. However, Windows is not open in the sense of the open standards considered elsewhere in this report: Microsoft does not allow participation in the development of Windows in the way that Standard Development Organisations do. In many ways this is a drawback: Microsoft's business partners will not automatically be aware of forthcoming changes in the standard in the way that would industry participants in an SDO. Furthermore, they might be concerned about being stranded with incompatible hardware or software.

C.71 The development of a new O/S version is a complex and resource-consuming process. An O/S consists of several modules of millions of lines of code dealing with several types of inputs from software applications and hardware. A module has to work correctly and also to fit perfectly with the other modules of the O/S.

C.72 The development of a proprietary O/S requires large teams of designers, programmers and testers organised by the O/S sponsor and can take several years. As an example, more than 200 designers, programmers and testers affiliated with Microsoft were involved in the development of Windows NT for a period of over five years. Around 15,000 testers volunteered to test the initial version of Windows NT.

C.73 Although facing similar complexities, the development process of an open source O/S (e.g. Linux sponsored by the web community) is very different. Open-source communities organised in the Internet are the primary developers of an open source O/S. As an example, around 4,000 programmers contributed to the development of Linux over the Internet and produced many utilities, libraries and modules, besides expanding the kernel.

C.74 The development of an open source O/S is much more structured than it seems at first glance. Many contributors are professional programmers affiliated to large corporations. Usually, a programmer or a contributing enterprise (such as SuSE) gives direction to the development process.[122] An individual programmer or a contributing enterprise first

120 Last visited on 1 February 2017, <http://itvision.altervista.org/files/Miguel.de.Icaza-What.Killed.the.Linux.Desktop.html>

121 Kshetri, N. (2005). Diffusion pattern of Linux: An assessment on major technology dimensions. First Monday, 10(8). <http://pear.accc.uic.edu/ojs/index.php/fm/article/view/1263/1183>

122 SuSE is a German-based, multinational, open-source software company that develops and sells Linux products to business customers.

posts a draft of a program, patch or new idea to the Internet. Depending on the popularity of the idea, other programmers contribute and develop the idea further. Open source communities and general public take care of the testing and fix errors. This ensures the constant improvement of the program through the web community.[123]

Effects of openness on innovation

C.75 There is empirical evidence on how the degree of openness of operating systems is related to development of technologies in the industry, from the hand-held computer segment. Boudreau (2008) analysed the operating systems for hand-held computers (PDAs) where different models had different degrees of O/S openness, ranging from granting access, devolving control, sharing IP and allowing outside contributions to the core platform. In some cases, O/S owners changed their approach to openness over time.

C.76 Variation in the extent of access over time and across platforms mainly related to whether and how operating system platform owners granted licenses to outsiders. This varied from outright exclusion to wide licensing to all comers. For example, despite expressed interest by outside manufacturers, Palm turned away would-be partners at several points in its history, even in its early days. Microsoft, for its part, began by licensing large OEM partners from its personal computing business, and only later opened licensing more widely and liberally. In 2009, Microsoft once again retreated to a more restrictive licensing approach.

C.77 In some cases, platform owners transferred IP, sharing "reference designs" or blueprints for fully-working devices. Devices built on reference designs could be differentiated by altering and customizing the design. The availability of reference designs lowered entry barriers, as modifying fully-working designs was much more straightforward than developing one's own design.

C.78 Operating system platforms were also opened to varying degrees. Control over operating systems remained consolidated under the platform owner for the most part. But in some cases, a share of the platform owner's equity was sold to independent hardware developers (e.g., Geoworks, Montavista, Psion and Palm).

C.79 Platform owners' vertical scope also varied, with Palm, Apple (Newton) and Psion (EPOC) being integrated into hardware development, alongside independent hardware developers.

C.80 Table 19 summarizes, with examples, some of the broad categorical distinctions between different modes and degrees of openness.

C.81 This study found that openness of the O/S to different hardware led to fivefold acceleration in development of new devices; as compared to a 20% acceleration associated with opening development of the operating system itself to other firms. In short, opening the control of the O/S does benefit innovation but the more important benefit arises from having an operating system that is compatible with hardware from multiple sources.

Release of a new O/S version

C.82 O/S sponsors periodically in turn new O/S versions with new capabilities, aiming to keep pace with technological developments in hardware and to introduce new functions serving changing user needs. In some cases, O/S sponsors have been suspected of introducing new versions solely

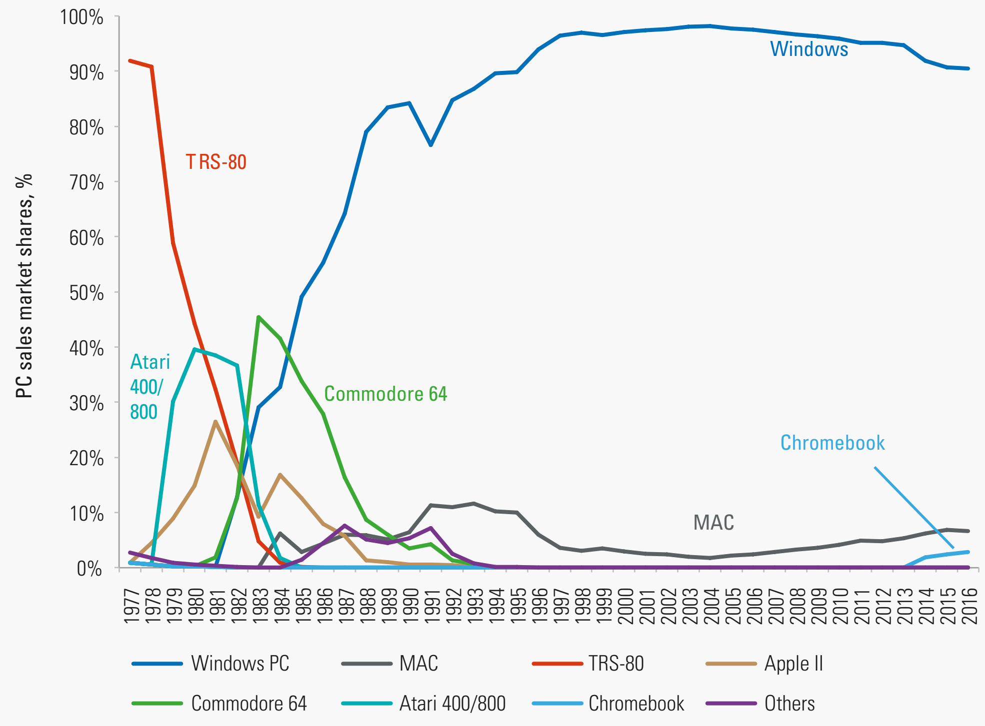
123 Gandal, N. (2002).

Table 19: Hand-held computers: examples of distinctions in openness policies

Opening the operating system platform				
		Monopoly control	Shared control	Share development
Opening complementary hardware	Shared IP	RIM (2004); Microsoft mobile (2003)		EPOC (2001) LynuxWorks (2005) Montavista (2005 Palm (2005) Other Linux Reference Designs
	Granted access	DOS GEOS Microsoft Mobile Palm (1997) Newton Penright RIM (2004) Windows	EPOC (1998) Palm (1999)	Montavista Mizi Linuette Lineo Other Mobile Linux Platforms
	Foreclosed entry	Cybiko GEO		Royal Consumer (2002) Other Custom Linux

Notes: The listing of a year indicates a change from an earlier policy to a different category
Source: Boudreau (2008).

Figure 36: PC O/S market shares, 1977 – 2016



Source: Adapted by CL from Dediu (2012).

to drive replacement sales. O/S sponsors collaborate closely with key hardware producers, such as producers of microprocessors, to optimize the performance of their O/S and the hardware.[124]

C.83 O/S sponsors provide hardware producers with a set of tools and libraries as an aid in the creation and update of their device drivers. A device driver is a software interface letting an O/S communicate with hardware. Hardware producers have to update their device drivers to ensure compatibility with the new O/S version.[125]

C.84 The firm sponsoring the O/S will normally want to develop its 'ecosystem' of software vendors, assisting them to make best use of the O/S's capabilities. To promote the development of application programs for its O/S, an O/S sponsor provides software vendors with a software development kit ("SDK") and an integrated development environment ("IDE"). A SDK contains documentation, header files, libraries, samples and tools required to develop application programs for the O/S,[126] whereas an IDE provides features for authoring, modifying, compiling, deploying and debugging software.[127]

C.85 To enlarge their application base, O/S sponsors also provide ISVs with tools to convert application programs written in foreign SDKs and IDEs to their own OS-specific language and structure. For example, Microsoft's Desktop Bridge helps ISVs to migrate their application program easily to Windows.

C.86 Backward compatibility ensures that users' investment in a particular O/S (such as application programs, training and other peripherals) are not stranded: users would be able to use their existing assets on a new version of the O/S. Backward compatibility facilitates adoption of the new O/S version and could therefore lead to technological development. However, backward compatibility has also its drawbacks, complicating the development of the O/S, making technological progress in developing the O/S itself more costly and thus perhaps slowing it down.[128]

Evolution of O/S market structure and innovation

C.87 There is little direct competition between the PC O/Ss but O/S developers are facing increasing challenges from mobile devices.

C.88 Since the launch of the IBM PC in the early 1980s, Microsoft has been the largest O/S sponsor in the market. Over the period 2002-2015, the share of Microsoft's Windows has been over 90%, with Apple's OS X and Linux at shares each less than 5%. Figure 36 also shows that Atari 400/800 and the Commodore 64 were market leaders for brief periods in the late-1970s and early 1980s.

124 Intel evangelists blog, available at <http://blogs.intel.com/evangelists/2015/10/02/intel-microsoft-new-experiences/> and Verge (2015).

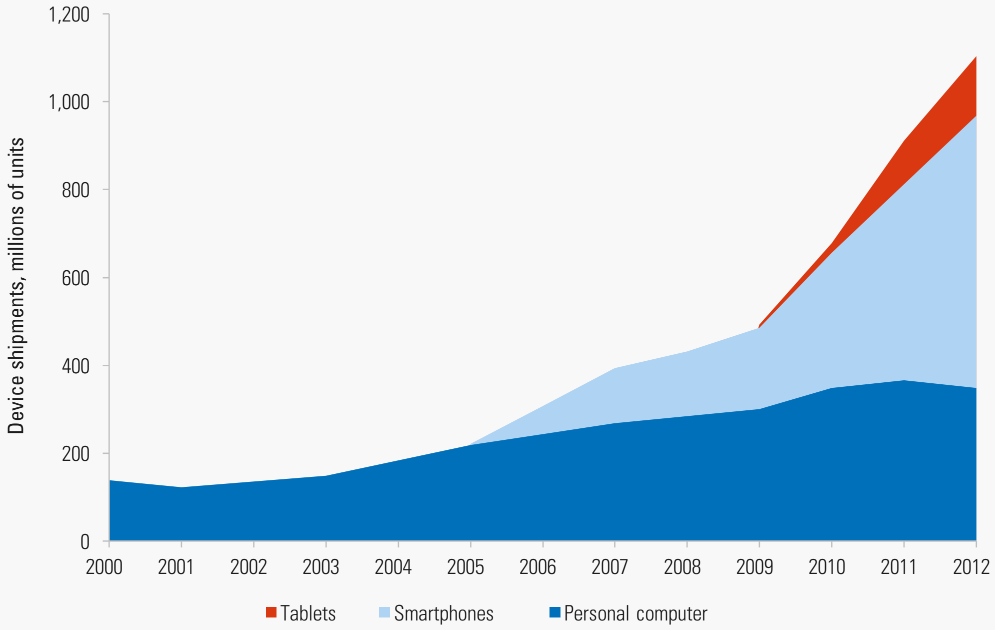
125 As an example, Microsoft delivers Windows Driver Frameworks (see Microsoft Driver Frameworks website <https://msdn.microsoft.com/en-us/library/windows/hardware/ff557565(v=vs.85).aspx>), and Apple provides (see Apple Developer website, <https://developer.apple.com/library/content/referencelibrary/GettingStarted/GS_HardwareDrivers/_index.html>

126 Such as Microsoft's Windows SDK and Apple's iOS SDK.

127 Such as Microsoft Visual Studio and Apple's Xcode IDE.

128 Gandal, N. (2002).

Figure 37: Global internet connected device shipments by device



Source: Adapted by CL from Blodget (2013).

C.89 Development of O/Ss for PCs illustrates many of the economic effects of standards – and also many of the effects of the control of a proprietary standard by a single company. An 'eco-system' of complementary products forms around an O/S and their incompatibility with other O/Ss creates network effects: users (application developers and end-users) both want to have an O/S on which there are many other users. These effects cause the market to tend towards concentration, possibly via a standards war.

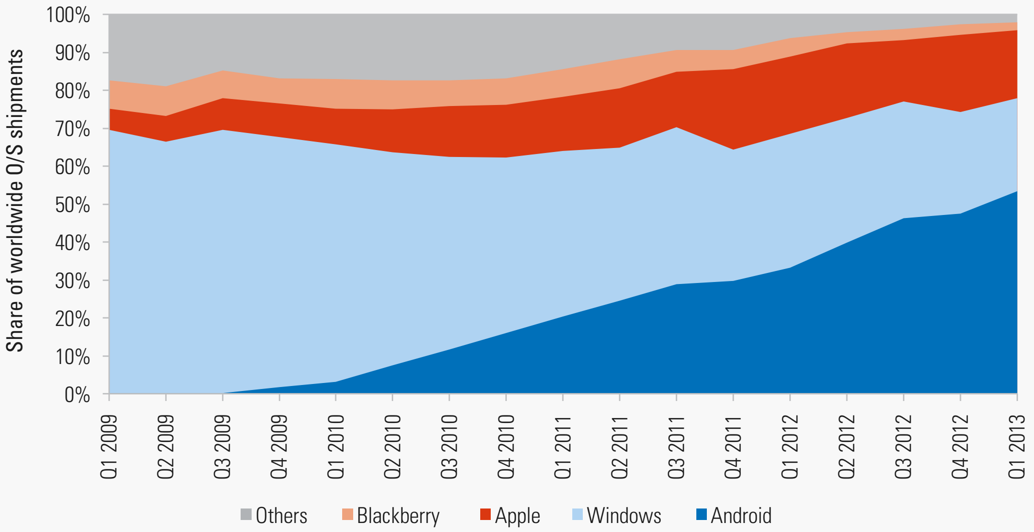
C.90 The more open approach taken by Microsoft compared to Apple may well have been a significant factor in its victory in that standards war. The Microsoft ecosystem overall may have been more innovative as well as cheaper because of the large number of competing hardware producers and applications developers. Windows has prevailed as the majority PC O/S despite state-sponsored, commercial and open-source challengers.

C.91 Microsoft's Windows has always been and remains a proprietary system. Many of the downsides of proprietary standards that we examine later in this report stem from standards wars – but in this case any such war was brief and won decisively by Microsoft very early on so by and large these direct effects have been absent. However, the company has been accused of taking advantage of its ownership of this central standard, often with the intention of maintaining the market position and relevance of Windows. Most famously, the US and European competition authorities have accused Microsoft of leveraging its O/S market power to extend monopoly to other, some nascent, businesses and of deliberately withholding compatibility information from competitors.

C.92 However, in recent years, the rapid expansion of the Internet from the mid-1990s onwards and the launch of tablets and smartphones - devices combining features of a PC with mobile use - in the 2000s disrupted the PC industry, including O/S. The processing power and functionality of mobile devices increased rapidly. They became powerful enough to run a full PC O/S, whereas cloud computing and online services enabled users to access data, media and application software from any device and anywhere. As a result, demand for mobile devices such as smartphones increased rapidly, while demand for PCs slowed (Figure 37).

C.93 New players specializing in Internet-related services and products (e.g. search, online advertising technologies and cloud) shift value away from the O/S level up higher in the stack to online services and the cloud, hurting pure O/S sponsors such as Microsoft. For example, Google licenses its Android O/S to mobile device makers for free and derives its main revenue from internet-related services and cloud. Perhaps as a result, Windows has not been successful in the smartphone market. So as smartphones and tablets have grown, the share of Windows in overall O/S shipments shrank from around 70% in 2009 to around 25% in 2013. Benefiting both from the rise of smartphones and increasing market share for mobile O/S, Google's Android has increased from almost nothing in 2009 to almost 50% in 2013 (Figure 38).

Figure 38: Worldwide O/S shipments 2009 Q1 – 2013 Q1

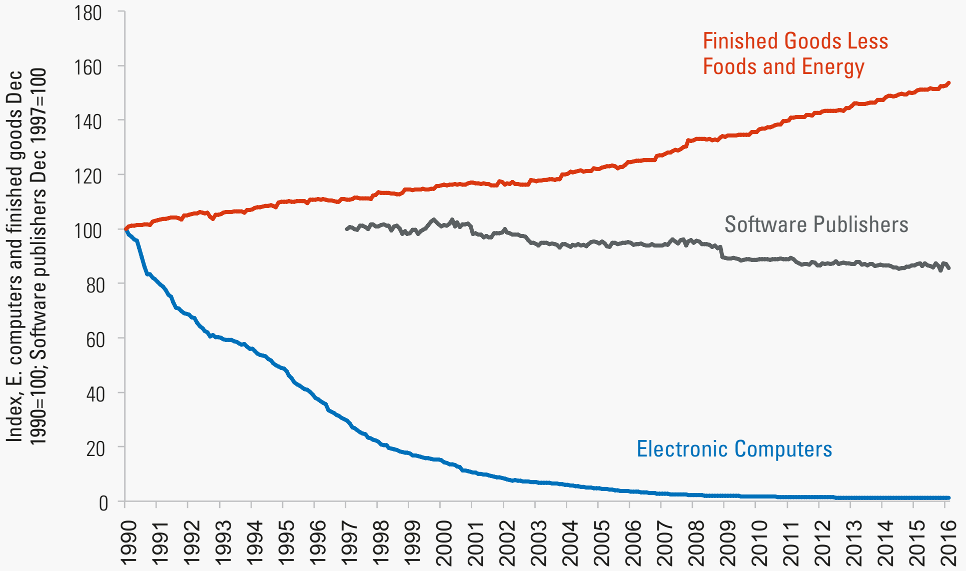


Source: Adapted by CL from the Business Insider (2013).

Impact on average prices

C.94 From a consumer's point of view, PC prices have fallen rapidly while productivity has increased, albeit not as dramatically as those in mobile telecoms. In the US, the Producer Price Index for electronic computers declined by close to 99% while that of finished goods (excluding food and energy) has increased by more than 50% since 1990 (Figure 39).

Figure 39: PC market quality-adjusted prices, US 1990-2016



Source: Federal Reserve Economic Data (PPI by Commodity for Machinery and Equipment: Electronic Computers WPU1151; PPI by Industry: Software Publishers PCU511210511210; and PPI by Commodity for Final Demand: Finished Goods Less Foods and Energy WPUFD4131).

Summary and conclusions

C.95 Standards can help create efficiency, but proprietary standards, managed by a single firm, are more likely to result in inefficient standards wars, the choice of inferior technologies and anti-competitive market structures and behaviour.

C.96 This case study illustrates two contrasting stories and market outcomes. The story of O/S on PC presents a relatively brief standard war with marginal adverse effects resulting in a proprietary standard: Microsoft DOS then Windows. Following the launch of the first PC in the early 1980s, Microsoft licensed its O/S to all PC manufacturers, charged low licensing fees and provided tools to application developers to facilitate positive network effects.

C.97 Microsoft's open ecosystem allowed it to become more innovative and adoptive to technological developments compared to its competitors with a closed ecosystem, such as Apple. Apple's iOS was less open than Microsoft's, and its releases were even less frequent that those of Microsoft's O/S-based rivals. As the 'gatekeeper', the standard holder has little incentive to innovate. Chip producers using Wintel's 'semi-open' standard introduced new chips more frequently compared to Apple's closed standards.

C.98 However, Microsoft's standard is open only in the sense that complementary products can freely be developed for it. It is not open in the sense that other firms can contribute innovations to the standard. The development of the PC industry suggests that this additional openness is not as important as openness to complements, but there have been widely publicised concerns about Microsoft's ability to use this ownership to reduce competition in other parts of the supply chain. Proprietary standards are also associated with slower innovation in the associated markets. For example, newer technologies, such as cloud computing, have relied on open-source programmes despite the strong dominance of proprietary software such as Windows in the PC market. Summarising the benefits of open source software for innovation, The Economist says, *"Without open-source programs like Linux, however, cloud computing would have been stillborn. Old-style "proprietary" software was too expensive and hard to adapt"* (The Economist 2016).

BELGIUM
Brussels
23 Square de Meeus
7th Floor
Brussels,1000
+32.2.274.22.50 main
+32.2.274.22.69 fax

FINLAND
Helsinki
Aleksanterinkatu 15 B
6th Floor
Helsinki, 00100
+358.9.3780.2644 main
+358.9.586.5030 fax

FRANCE
Paris
22 Place de la Madeleine
4th Floor
Paris, 75008
+33.1.53.05.36.15 main
+33.1.53.05.36.16 fax

GERMANY
Berlin
Kontorhaus Mitte (Haus A)
Friedrichstrasse 187
Berlin 10117
+49.30.288.744.250 main
+49.30.288.744.244 fax

Düsseldorf
Kö-Bogen
Königsallee 2b, 5th Floor
Düsseldorf, 40212
+49.211.88.242.235 main
+49.211.88.242.200 fax

SPAIN
Madrid
Paseo de la Castellana 7
9th Floor
Madrid, 28046
+34.91.586.10.00 main
+34.91.586.10.59 fax

UNITED KINGDOM
London
200 Aldersgate
Aldersgate St.
London, EC1A 4HD
+44.20.3725.9000 main
+44.20.3725.9099 fax

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