Centre on Regulation in Europe

Improving network industries regulation

An Integrated Regulatory Framework for Digital Networks and Services

A CERRE Policy Report

Appendix 2: Imagine 2025

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Table of contents

About the author

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1. Introduction

This paper explores the developments in the electronic communications industry towards the 2025 horizon. The image of the future is constructed based on an exploration of the trends that are underlying current developments. This image is complemented with a reflection on innovation, by looking back ten years to anticipate what might happen in the coming ten years.

The broader context applied derives from the reasoned history of technological developments, from the First Industrial Revolution in the UK to the current day ICT-driven revolution being global in nature. Each subsequent technological revolution reflects a degree of regularity as well as unique features. We use this stylised model of economic developments to capture the 'installation' and 'diffusion' of a new techno-economic paradigm.

The core input of the current techno-economic paradigm are the 'chips', the silicon based processing entities which double in capacity approximately every 18 months while costs remain roughly the same. This regularity drives both the supply side and the demand side of the electronic communications industry. We explore the implications of this so-called Moore's Law for both the fixed and mobile market.

For the fixed market it implies an extension of the 'life of copper networks' and for the mobile market it implies development towards a 'virtual utility'.

The anticipated technological developments form the bases for reflections on the likely changes in industrial organisation, including the implications for regulation. Special attention is given to various forms of convergence.

The report concludes with a reflection on the robustness of the 2025 image.

2. Economic development: showing regularities

Economic developments are not smooth, but are characterised by ups and downs. Changes in demand typically result in investment cycles, such as the popular 'pig cycle'. In addition, economists have identified an inventory cycle (the so-called Kitchin cycle of 4-5 years), a capital goods cycle (Juglar cycle of 7-11 years) and a building cycle (Kuznets cycle of 15-25 years) (De Wit, 1994).

Next to these relatively short cycles, a long wave in economic development covering 40-60 years has been identified, the so-called Kondratieff cycle. This cycle has long been associated with economic crisis on the one hand and expansion related to technology and trade on the other (Freeman, 1998). Schumpeter made the link to innovation, and in particular the clustering or discontinuities in technical innovation, as the driving force behind the long wave in economic development (Kleinknecht, 1987). Kleinknecht also points to other, complementary forces that are driving the long wave, identified by Van Gelderen and De Wolff: "In each upswing of the long wave, the production of investment goods will expand more rapidly than the production of consumer goods" (Kleinknecht, 1987 p3-4). There is also the hypothesis by Van Gelderen on the availability of cheap loan capital together with a low price level at the end of a long wave depression. From his research Kleinknecht concludes that Schumpeter's hypothesis about long waves in economic life and an uneven distribution over time of radical innovations can be defended, not only in time but also in certain sectors. The theoretical explanation is to be found in the: "…reallocation of R&D and other investments towards new technological paradigms in response to the rien ne va plus during the long wave depression" combined with "...an endogenously caused over-expansion and depreciation of capital stock… [that] is caused by an expansionary self-ordering feedback loop: to satisfy demand for investment goods from the consumer goods sector, the capital goods producing sector itself has to expand its capacity, ordering capital goods for the production of capital goods." Furthermore, Kleinknecht argues, "…the hypothesis seems plausible that prolonged depressions not only trigger a reallocation of innovative resources but also create strong pressure towards social, political and institutional change". (Kleinknecht, 1987 p197-213) Freeman and Soete underline this broader perspective that: "…clusters of radical technical innovations do also lead to major disruptions not just in the production sphere but also in the broad social, institutional and organisational sphere" (Freeman & Soete, 1997 p330).

Of particular interest in our project is the link between Schumpeterian innovation, the emergence of new industries and the building of new related infrastructures, a link provided by De Wolff. This linkage is made more explicit through the interpretation of regularities in history by Freeman, Louçã and Perez. Freeman and Louçã have further explored the notion of Long Waves and thereby argued a case for the application of 'reasoned history' as "…an approach to economic history including technological innovations, structural changes, and the co-evolution of economic and social movements within the framework of institutional settings and modes of regulation" (Freeman & Louçã, 2001 p123).

On the basis of the Theory of Reasoned History, Freeman and Louçã explore recurrent phenomena in history, i.e. the successive Industrial Revolutions. See Table 1 for a condensed summary of the Kondratieff waves as analysed and described by Freeman and Louçã (Freeman & Louçã, 2001 p141).

Table 1: Condensed summary of the Kondratieff waves

Constellation of technical & organisational innovations	Examples of highly visible, technically, successful, & profitable innovations	'Carrier' branch and other leading branches of the economy	Core input and other key inputs	Transport and communi-cations infrastructures	Managerial and organisational changes	Approx. Timing of the 'upswing' (boom) 'down swing' (crisis of adjustment)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1. Water-powered mechanisation of industry	Arkwright's Cromford mill (1771) Henry Cortt's'puddling' process (1784)	Cotton spinning, Iron products, Water wheels, Bleach	Iron Raw cotton	Canals Turnpike roads Sailing ships	Factory systems Entrepreneurs Partnerships	1780s-1815 1815-1848
2. Steam-powered mechanisation of industry and transport	Liverpool-Manchester Railway (1831) Brunel's 'Great Western' Atlantic steamship (1838)	Railways & railway equipment, Steam engines, Machine tools, Alkali industry	Iron Coal	Railways Telegraph Steam ships	Joint stock companies Subcontracting to responsible craft workers	1848-1873 1873-1895
3. Electrification of industry, transport and the home	Carnegie's Bessemer steel rail plant (1875) Edison's Pearl St. New York Electric Power Station (1882)	Electrical equipment Heavy engineering Heavy chemicals Steel products	Steel Copper Metal alloys	Steel railways Steel ships Telephone	Specialised professional management systems 'Taylorism' giant firms	1895-1918 1918-1940
4. Motorisation of transport, civil economy, and war	Ford's Highland Park assembly line (1913) Button process for cracking heavy oil (1913)	Automobiles, Trucks, Tractors, tanks, Diesel engines, Aircraft Refineries	Oil Gas Synthetic materials	Radio Motorways Airports Airlines	Mass production and consumption 'Fordism' Hierarchies	1941-1973
5. Computerisation of entire economy	IBM 1401 and 360 series (1960s) Intel microprocessor (1971)	Computers, Software, telecommunication equipment Biotechnology	'Chips' (integrated circuits)	'Information Highways' (Internet)	Networks; internal local, and global	1973-??

Source: Freeman & Louçã, 2001

In pointing to recurrence, they caution the reader: "we should re-emphasise here our belief that this recurrence is limited in scope and content. Each technological revolution and each phase of economic growth has its own unique features. This does not mean, however, that we cannot learn a great deal from even this limited recurrence as well as from unique events…. …The work of Carlota Perez (1983, 1985, 1988) on long waves has shown that, even if identical behaviour is ruled out, as it must be, there may still be striking similarities or dissimilarities and some hidden ones too, which are helpful in understanding the phenomena and even in making probabilistic forecasts and indications for policy" (Freeman & Louçã, 2001 p130-1).

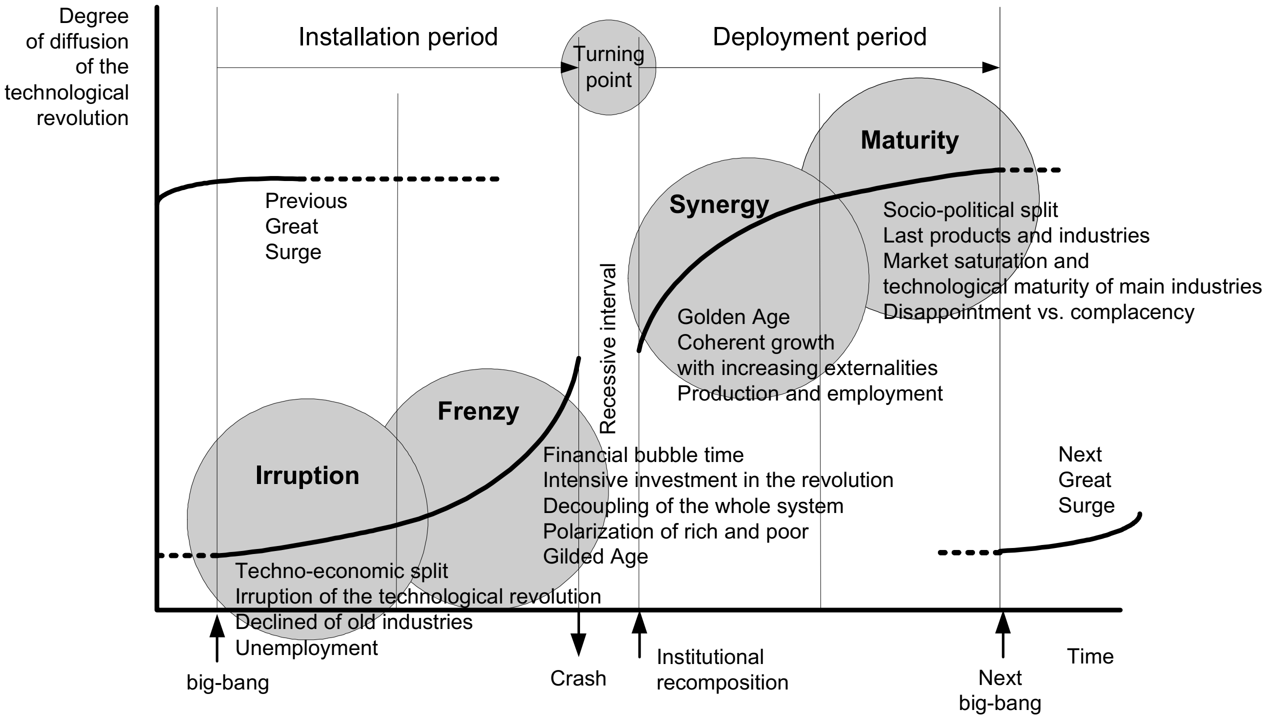
In her 2002 book 'Technological revolutions and financial capital: The dynamics of bubbles and golden ages', Perez has expanded on her suggestions captured by Freeman. In observing the 'boundless rise of two forces: the information revolution and financial markets' in the last quarter of the twentieth century, she argues that: "productivity explosions and bursts of financial excitement leading to economic euphoria and subsequent collapse of confidence have occurred together before. They are interrelated and interdependent phenomena; they share the same root cause and are in the nature of the system and its workings. They originate in the way technologies evolve by revolutions, in the peculiar manner in which these great upsurges of wealth creating potential are assimilated by the economic and social system and in the functional separation of financial and production capital" (Perez, 2002 pxvii). Based on historical analysis she shows that the sequence of 'technological revolution – financial bubble – collapse – golden age – political unrest', is recurring about every half century. This recurrence is considered to be based on: "causal mechanisms that are the nature of capitalism, which stem from the features of the system, which interact with and influence one another:

1. The fact that technological change occurs by clusters of radical innovations forming successive and distinct revolutions that modernise the whole productive structure;
2. The functional separation between financial and production capital, each pursuing profits by different means; and
3. The much greater inertia and resistance to change of the socio-institutional framework in comparison with the techno-economic sphere, which is spurred by competitive pressures." (p5-6)

In the early phases there is the battle of the new paradigm with the power of the old paradigm, which is "ingrained in the established production structure and embedded in the socio-cultural environment and in the institutional framework." When this battle is won the new paradigm diffuses across the whole of the economy and society. Hence, the diffusion of the new paradigm can be seen as two distinct periods, the 'installation period' and the 'deployment period', both typically lasting 20-30 years. The 'turning point' from the installation to the deployment is "usually a period of serious recession, involving a re-composition of the whole system, in particular of the regulatory context that enables the resumption of growth and the full fructification of the technological revolution." (p36)

The ensuing life cycle of a technological revolution is shown Figure 1.

Figure 1: Great Surge model



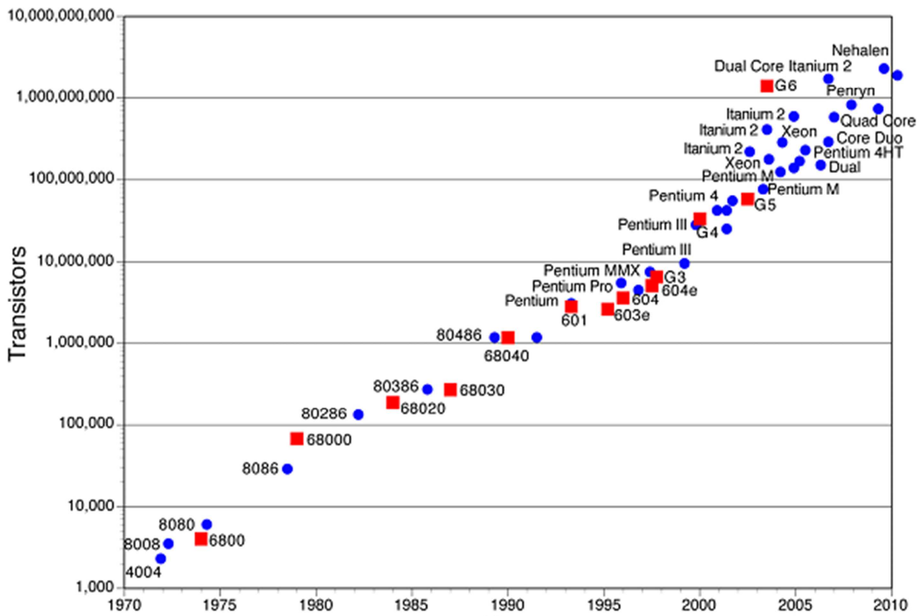
Source: Perez, 2002

3. The deployment period of the ICT-driven techno-economic paradigm

The most recent surge is related to the ICT-driven technological revolution, or in terms of Perez the ICT-driven techno-economic paradigm (TEP).

The core input of the current TEP are the microelectronic chips, co-invented by Kilby at Texas Instruments and Hoerni and Noyce at Fairchild in 1957-1959. Since that time progress has been unabated, which led to Moore's Law stating that silicon based capabilities are doubling in performance at the same costs about every 18 months (Moore, 1965).[1] See Figure 2 as an illustration showing the number of transistors that make up the microprocessors produced by Intel and Motorola, shown for the period 1970-2010.

Figure 2: Moore's Law reflected in micro-processors by Intel and Motorola, 1970-2010



Source: *http://sites.psu.edu/summer2013art003lvj5077/wp-content/uploads/sites/3861/2013/05/Moores_Law.jpg*

The core input of the current TEP are the microelectronic chips, co-invented by Kilby at Texas Instruments and Noyce at Fairchild in 1957. Since that time progress has been unabated, which led to Moore's Law stating that silicon based capabilities are doubling performance at the same costs about every 18 month (Moore, 1965). This is not a law of nature but it captures the outcome of innovation and engineering prowess in the microelectronics industry. The invention of the microprocessor in 1973 by Hoff at Intel is

[1] For the meaning and development of Moore's Law see "Fifty years of Moore's Law" by Mack (2011) and by Golio (2015) and "The multiple lives of Moore's Law" by Mack (2015).

considered the milestone marking the beginning of the ICT-driven techno-economic paradigm – the 'big bang' and the period of eruption as indicated in Figure 1. Moore's Law is both supply-side and demand-side driver.

The installation period was first characterised by an IT-based revolution in the 1980s, with deep investment in computing power in anticipation of significant productivity improvements. However, at the aggregate level no major improvements could be observed. This led to the formulation by Solow of the productivity paradox. Firm level analysis by Brynjolfson et al. has shown that next to investment in computer hardware, complementary investments are required in software, in human resources and in the redesign of business processes before the envisaged productivity improvements can be realized (Brynjolfson, 1992; Brynjolfson & Hitt, 1998).

The IT-based revolution was followed by a CT-based revolution in the 1990s. This period was characterised by a boom in communications infrastructure spending, fueled by a rise in bandwidth demand through the emergence of the Internet and through the popularity of mobile communications. The euphoric period ended with a crash in the year 2000. We are now in the middle of the deployment period, which lasts approximately 30 years. This is the period in which the revolution spreads further, from the ICT-producing and ICT-intensive industries affected during the installation period, to all other economic sectors and across society at large.

This deployment is characterised by constant reciprocal action between the three spheres of change: technological, institutional and economic. The process of change reflects the transformation from the previous Fordist-based techno-economic paradigm and its best practices, to the current ICT-based techno-economic paradigm. Table 2 reflects the main differences: at Level 1 in the core technology and infrastructure; at Level 2 the industrial organisation; and at Level 3 the 'common sense' principles or best practices (derived from: Perez, 2002). For a more detailed comparison see Lemstra (2006).

Table 2: The three levels in the 4th and 5th Techno-Economic Paradigm

	Techno-Economic Paradigm	
	4th Fordist	5th ICT
Level 1	**Technology & Infrastructure**	
A constellation of technologies, products and industries with wide generic applicability, and a supporting infrastructure	Internal combustion engine (for autos, tractors, electricity, generation, aeroplanes, etc.)	Micro-processor (as information processing engine)
	Oil and gas as fuels	Data as fuel
	Petrochemical industry (refinery, synthetic materials and chemicals)	Communications and Information Technology industry (hardware, software, services)
	Motorways, airports, airlines	Internet, broadband access
Level 2	**Organisation**	
An organisational model for best practice in all productive activities	Dedicate mass production	Adaptable production systems
	Compartmented hierarchical pyramids	Flexible networks, flat and broad ranging
	Materials and energy intensive	Information intensive
Level 3	**Common sense' principles**	
A general set of 'common sense' principles for guiding organisational and institutional innovation	Centralisation	Decentralisation
	Separation of work and organisations by function	Re-integration of functions
	Massification	Diversification
	Negotiation of conflicts	Consensus building
	Regulation and supervisory control	Guidelines, trust and monitored control

Source: Perez, 2002

4. Core input: All-things-digital, all-things-packet

The 'core input' (see Table 1) to the current techno-economic paradigm (TEP) – the use of integrated circuits – has led to the 'digitisation' of all information inputs, which subsequently allowed for digital transmission, storage and processing of information. During the installation period of the current TEP, the transmission and switching in the communications networks have changed from analogue to digital. With the introduction of the Internet in the second half of the 1990s came a further change from circuit-mode to packet-mode switching. And as the Internet is subsuming all types of previously dedicated networks for information transport and communication, the Internet has become the 'transport and communications infrastructure' of the current TEP. The use of the TCP/IP protocol stack, being central to the Internet, has effectively decoupled the applications and services from the characteristics of the underlying networks, whether they are fixed or mobile, and whether they use copper, fibre or radio waves as the transport medium.

4.1 From physical to virtual: information rules apply

In contrast to the earlier techno-economic paradigms, where the 'propellant' was physical, i.e. water, steam, electricity and oil, the current paradigm is propelled by information. With the low transportation costs and extremely low reproduction costs of information the economics of this revolution are different from previous technological revolutions: today 'information rules for the networked economy' apply. Examples of these 'information rules' are (Shapiro & Varian, 1999):

- Technology changes. Economic laws do not;
- Information is an experience good, consumers must experience it to value it;
- Information should be priced for its value not its costs;
- The Internet makes it easy to personalise information products, thereby adding value;
- For digital content, production is reproduction;
- Network effects lead to demand side economies of scale and positive feedback;
- Supply-side and demand side economies of scale combine to make positive feedback in the network economy especially strong;
- Positive feedback makes the strong grow stronger… …and the weak grow weaker.

The 'information rules', often in combination with the ubiquity of the Internet, have changed in a fundamental way how business is conducted: it has caused the demise of industry sectors, such as that for music recording and playback equipment; it has changed business paradigms, e.g. from 'print-distribute' to 'distribute-print'; it has led to disintermediation, e.g. in the travel business. The full diffusion of the new techno-economic paradigm will require reconceptualisation of all activities to be able to reap the full benefits.

4.2 Implications for telecommunications

While electronic communications infrastructures are subject to network effects, it is the services and application that are provided over these physical infrastructures that are subject to the 'information rules for the networked economy'. This applies in particular to the so-called 'over-the-top' (OTT) services and applications.

By allowing users to connect for a fee to their access network, telecom operators, or rather Internet service providers (ISPs), grant these users access to the globally interconnected communication network, i.e., yesterday's telephone network and today's Internet. The ISPs thereby allow the access users to benefit from the global network effects that have been realised, which can be called the *network-level* network effect.

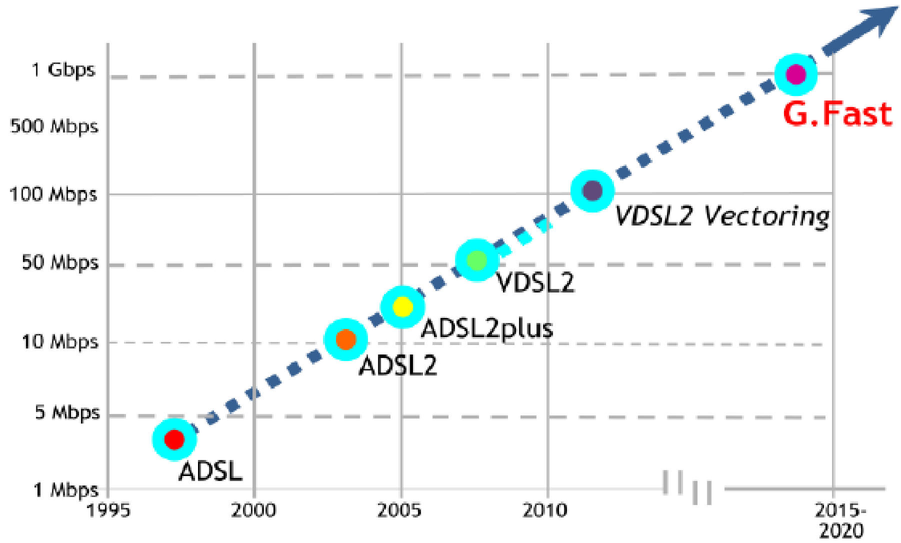
Thanks to the globally interconnected Internet, whereby all communications firms are complying with the Internet protocol stack, this interconnection is irrespective of geography. Using this connectivity, the OTT-services firms can deliver OTT-services to their subscribers wherever they are connected to the Internet. In this way a secondary network effect can be realised among users of the online service – a *service-level* network effect. The size of this network effect depends on the number of users of the specific online service, e.g. the number of WhatsApp users. In principle, it can replicate the size of the *network-level* network effect.

At the network level, 'all things digital' and 'all things packet' are also leading to various forms of convergence at the services level. For further discussion, see Section 7. The virtualisation as it applies to mobile communications is the topic of Section 6.4. But first we will explore the implications of Moore's Law on fixed networks, reviewing the past and the expectations for the future in Section 5. This is followed by a discussion of the impact of Moore's Law on mobile networks in Section 6.

5. Moore's Law and fixed networks

The progress in signal processing power is also visible in fixed broadband networks. See Figure 3 for an overview of the theoretical rates of the various DSL access technologies.

Figure 3: Evolution of DSL data rates, 1995-2020



Source: FttH Council Europe, 2014

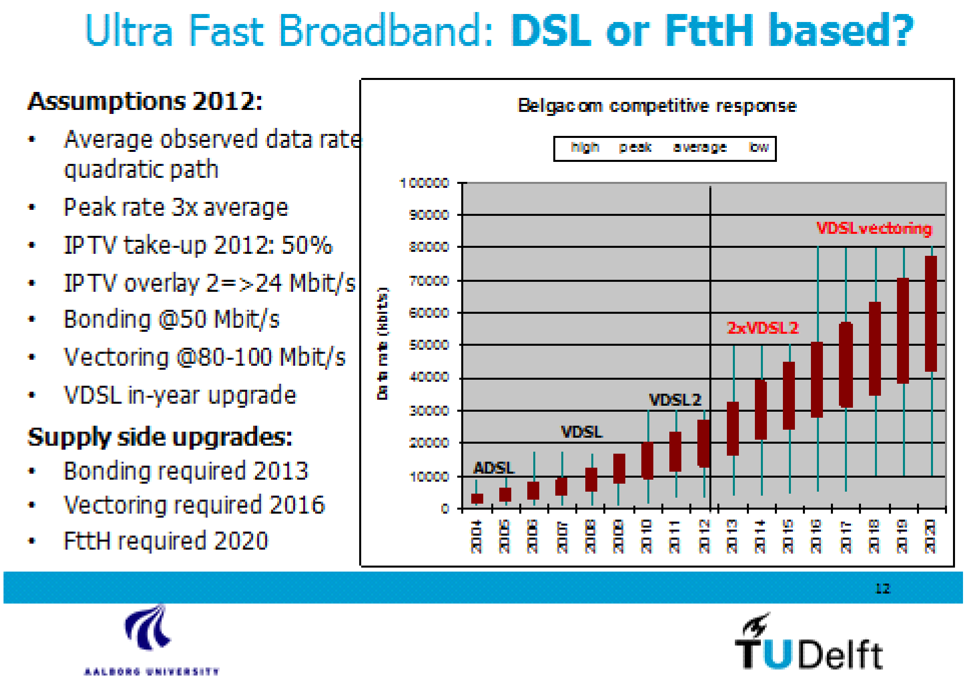
5.1 Developments in the PSTN

In 2012, a scenario was developed using Belgium and incumbent operator Belgacom (now Proximus) as an example to explore when copper would 'run out of steam' and fibre to the home deployments would be required to keep up with growing demand - see Figure 4 (Lemstra, 2012). At that time VDSL2 was widely deployed and bonding was considered a readily available option to expand capacity in the near future, while vectoring was a promising new solution under development. Based on the demand growth scenario the network would 'run out of steam' by 2020. Considering the significant lead times in deploying FttH, under this scenario Belgacom should start the roll-out of FttH not later than 2017.

In 2015 the scenario was updated using actual data rates measured by Akamai over a much longer period. It appeared that the average data rate was estimated as too high while the average peak data rate was estimated too low. The ratio between average and peak ranged in practice from 3x to 5x.

According to Akamai, the average connection speed is low because of: (1) parallel requests, whereby an average webpage generates 90 requests for content; i.e. involving relatively small files as many components make up a webpage; each session being too short to ramp up to maximum speed; and (2) IP address sharing, whereby multiple devices use an internet connection with an unique IP address, with simultaneous requests sharing the available bandwidth. The average peak connection speed reflects the highest connection speeds from each unique IP address. Thereby it is representative of internet connection capacity. It reflects larger files, such as software updates occurring late at night (Akamai, 2015).

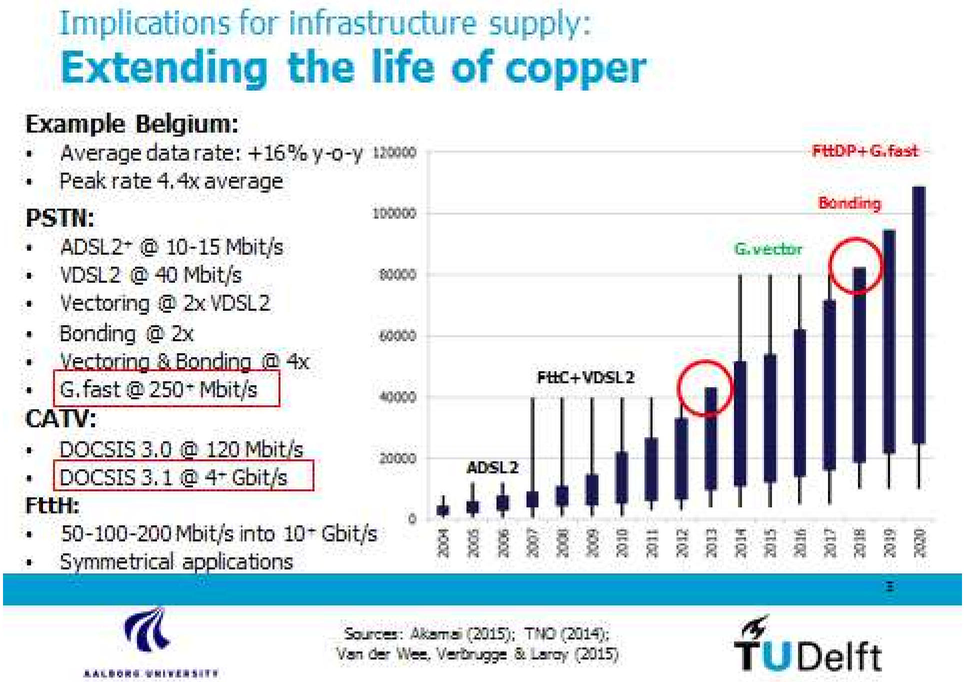
Figure 4: The useful life of copper, 2012 perspective



Source: Lemstra, 2012

In the updated scenario the data rates are extrapolated using the 16% annual growth rate representative for the past 5 years. Moreover, the much earlier and wide deployment of vectoring by Proximus is reflected. The new scenario suggests that the use of vectoring runs out of steam by 2018. Looking into the future, bonding is still a readily available option but it comes at doubling the cost. Moreover, progress on the G.fast standard suggests possible large scale deployments within the 2020 timeframe to cater to growing demand –see Figure 5 (Lemstra, 2015). Note that G.fast implies bringing fibre closer to the home, from the cabinet to the distribution point.

Figure 5: The useful life of copper, 2015 perspective

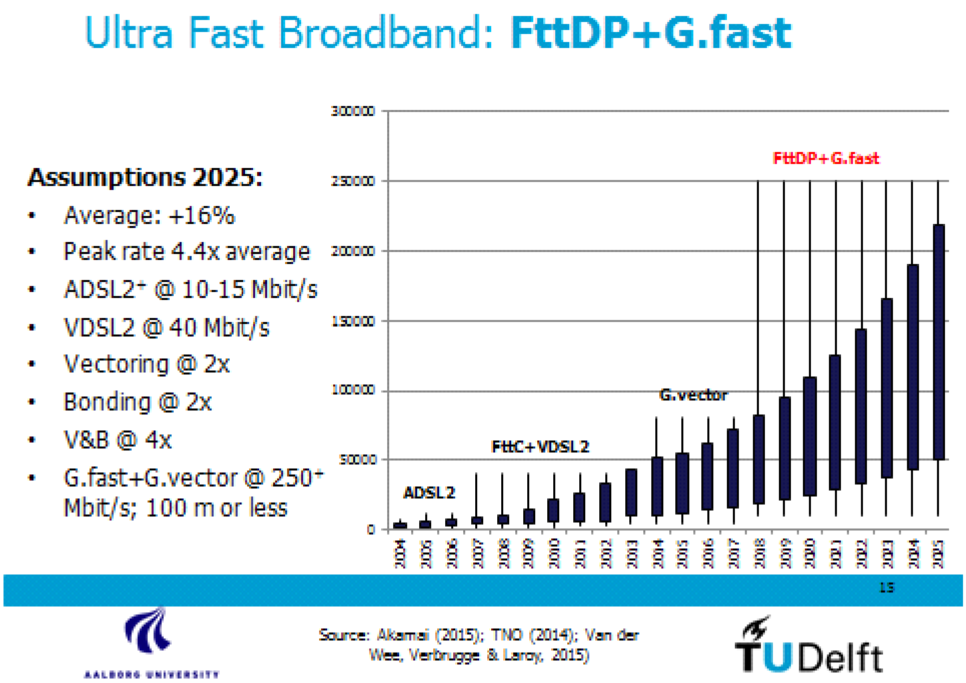


Source: Lemstra, 2015

Staying with the Belgium-Proximus scenario and applying the current growth rate of 16% for average data rates[2], the scenario projects an average data rate of 50 Mbit/s and an average peak rate of approximately 220 Mbit/s for the year 2025 - see Figure 6. With many G.fast trials underway and the first commercial deployments being announced, broad deployment of G.fast could start in 2018, thereby solving the looming VDSL2+G.vector bottleneck in the 2015 scenario. The predicted capacity of FttDP+G.fast+G.vector on copper loops of 100 meters or less is given as at least 250 Mbit/s symmetrical. Under this scenario the useful life of copper would be extended well beyond 2025. The deployment of fibre would have to be extended to the distribution point, the basement of a multi-dwelling unit or the street access of individual homes, thereby reducing the serving areas to micro-nodes of 1-16 subscribers.

[2] This growth rate applies to the Internet in general. The derived CAGR of 16% is comparable to the growth rate of 15% for video bandwidth over the period 2011-2020 as used by Alcatel-Lucent Bell Labs in its outlook. (Alcatel-Lucent, 2013) It is consistent with the data reported by Cisco for Western Europe over the period 2014-2019: broadband data rates growth at 18%; total IP traffic at 21% CAGR; consumer web, email and data traffic at 13%; consumer file sharing traffic -3%; consumer internet video traffic 31%; consumer managed IP traffic 12%; and business IP traffic 18%. (Cisco, 2015)

Figure 6: The useful life of copper, 2025 perspective



Source: Lemstra, 2015

5.2 Developments in the CATV network

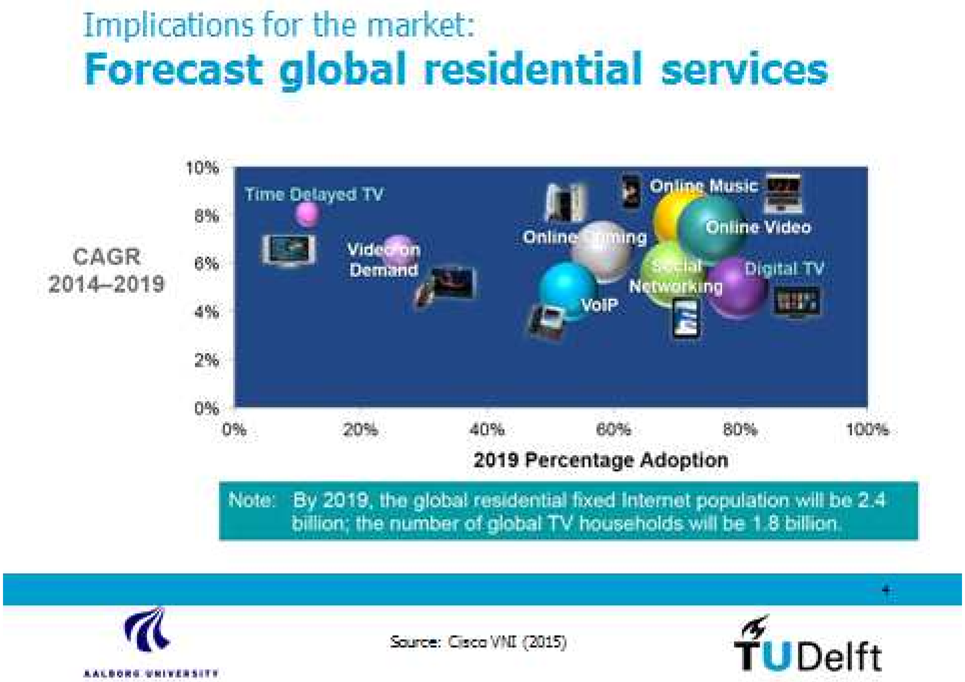
The CATV-cable network operators, such as Telenet in Belgium, have always been in a more comfortable position as the coax cable has an inherently higher bandwidth. The use of DOCSIS 3.0 modems allowed them to offer data rates well above 100 Mbit/s, though actual rates may be lower due to the sharing of the final part of the access among multiple subscribers. The capacity can be increased by reducing the group size and/or using more capacity in the tertiary network.

Looking into the future, the availability of DOCSIS3.1, which implies a transition to OFDM-based modulation techniques, is being advertised with a maximum download rate of 10 Gbit/s and upload of 1 Gbit/s (NLkabel, 2014; Rohde&Schwarz, 2015). Hence, CATV-cable operators are able to stay well ahead of the rates that can be offered on twisted pair copper.

Note that the Belgium-Proximus scenario can be considered typical for West-European countries, whereby Belgium is characterised by a strong push of IP-TV by the incumbent operator, as well as an early and wide deployment of vectoring.

Figure 7 presents Cisco's forecast for residential services in terms of growth rate and penetration for the 2019 horizon. In 2019, 4k video is expected to account for 21% of all video-on-demand traffic (Cisco, 2015).

Figure 7: Forecast global residential services, 2019



Source: Cisco VNI, 2015

The question for the 2025 scenario is whether the capabilities of G.fast and DOCSIS3.1 that could be provided will be implemented by network operators. For the CATV networks a similar argument applies as for the mobile networks. As the access capacity is shared among multiple users, the use of higher systems capacity is always attractive as it allows an increase in higher data rates to be offered to end-users, without the need to decrease the sharing rate. As the former PSTN-networks are based on point-to-point connections, deployment is more directly related to end-user demand and, where applicable, competitive pressure from CATV networks.

In most forecasts, video is still considered the main driver of high-end demand. Here, end-user behavior appears as somewhat paradoxical. At the fixed network side we can observe an uptake of higher definition TV, while at the mobile network side we see end-users watching TV on very small screens. However, if higher quality and larger screens become available, the high-end of the market will readily adopt these improvements, such as the adoption of tablets and the latest versions of smart phones.

Technological developments are also somewhat paradoxical. At the same time as higher data rates are made available, Moore's Law provides for more powerful encoding and compression algorithms reducing the need for higher data rates.

Nonetheless, the combination of Moore's Law and competitive pressure appears to have led to a certain regularity in the market. On the one hand newer and more capable end-user devices are introduced at roughly the same price as earlier generations, and on the other hand higher data rates are also offered by network operators at roughly the same price.

Given the enduring nature of Moore's Law we may expect this regularity to continue, most likely into the 2025 time frame.

In terms of industry structure, this outlook suggests a continuation of the role of legacy networks, the incumbent PSTN and CATV networks both turned into All-IP networks. With the introduction of FttC+VDSL, the network economics already forced most alternative operators to climb down the 'ladder of investment', from physical unbundling to virtual unbundling. With G.fast this trend is being re-enforced, as the fiber-based aggregation points are moving deeper into the access network, each capturing fewer subscribers.

With infrastructure-based competition being well established where legacy networks are present, the rational for asymmetric access regulation has disappeared. Combined with the notion that 'two may not be enough' to assure a well-functioning competitive market, the question to be answered at the outset of the next regulatory period is whether symmetric access regulation should be applied.

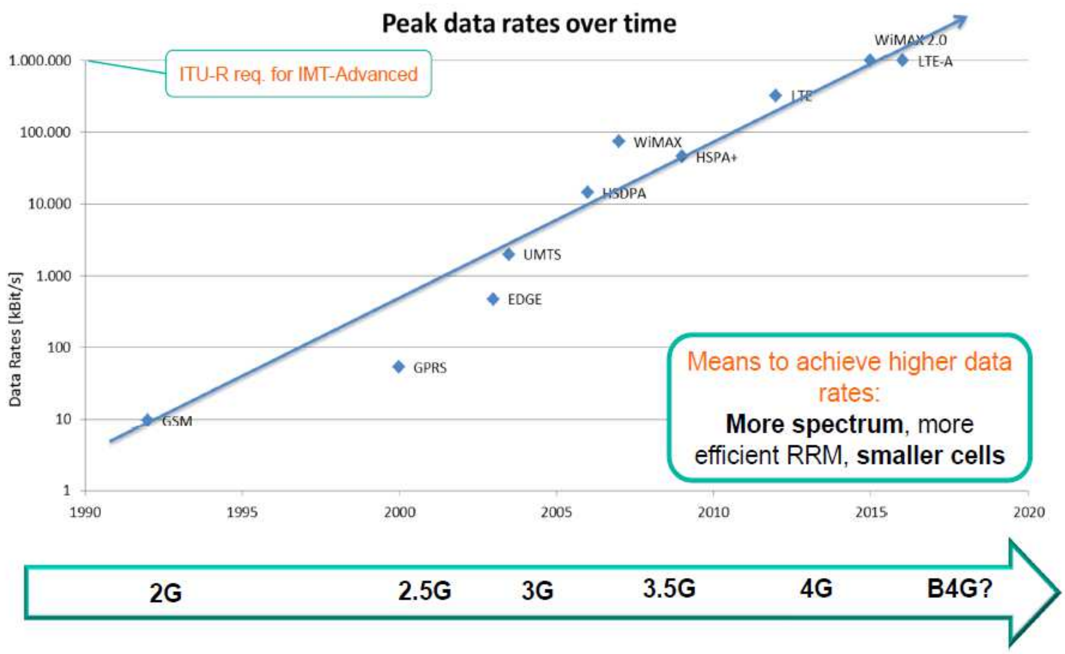
Where fiber to the home is deployed, alternative access is typically dependent on the deployment of point-to-point architectures. With the prospect of wavelength multiplexing on passive optical networks, PON may be able to provide for alternative access. This would allow for competition at a more attractive cost level.

Where FttH is realised through state aid, open access is typically a condition for obtaining the funds.

6. Moore's Law and mobile networks

Moore's Law is very clearly reflected in the growth in data rates, in particular those achieved in mobile communications - see Figure 8 (Niemegeers & Heemstra de Groot, 2015). This is essentially the result of more capable signal processing allowing for higher order modulation techniques to be applied. We may expect this trend to continue.

Figure 8: Peak data rates in mobile, 1990-2020



Source: Niemegeers & Heemstra de Groot, 2015

6.1 Next generation mobile: 5G - another application in the cloud

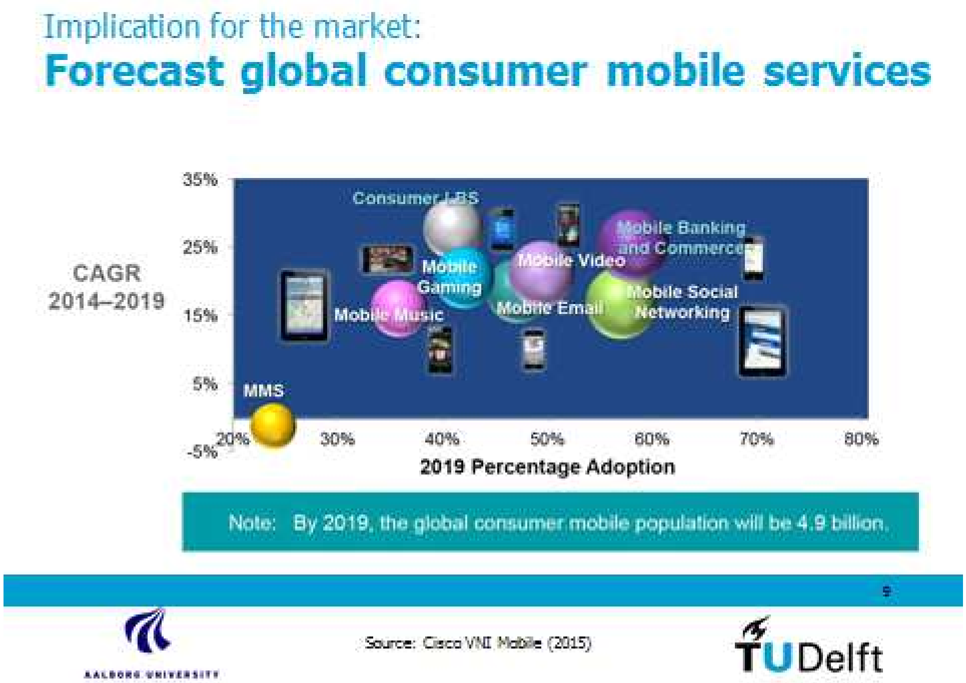
The succession of generations of cellular mobile networks shows a high degree of regularity: 1G was introduced in the early 1980s, 2G in the early 1990s, 3G in the early 2000s and 4G deployment started in 2010. Hence, it should not come as a surprise that the introduction of 5G is foreseen from 2020 onward (4G Americas, 2014a; 5G Infrastructure Association, 2015; ITU-R, 2015).

5G represents a next step in the technological evolution: 1G was dedicated to telephony, 2G started as capacity expansion for telephony to which a packet-switched overlay network (GPRS) was later added to provide access to the Internet. 3G was designed for both voice and data communication (implemented through resp. circuit switching and packet switching). High demand for Internet access required regular upgrades, from HSPA (high speed packet access), through HSPA$^+$ and HSPA Advanced. This also accelerated the transition to the next generation of mobile technology – 4G – also known as Long-Term

Evolution (LTE), which is packet switched only.[3] Again, intermediate enhancements were made based on regular updates of the specifications. The upgrade to LTE Advanced with a common air interface, introducing data rate enhancement through carrier aggregation, was first introduced in 2013. It provides a peak cell capacity of 1.2 Gbit/s.

These network enhancements are intended to keep up with the growing end-user demand across a range of services. Figure 9 provides Cisco's forecast for growth and penetration of global consumer mobile services towards 2019 (Cisco, 2015).

Figure 9: Forecast global mobile consumer services, 2019



Source: Cusci VNI Mobile, 2015

Note that all but one of the services shown are applications which use the mobile infrastructure to obtain access to the Internet. Only MMS is an integrated service, which is shown with a negative growth rate. Moreover, mobile telephony and SMS as distinct services have disappeared from the radar screen, having become part of mobile social networking.

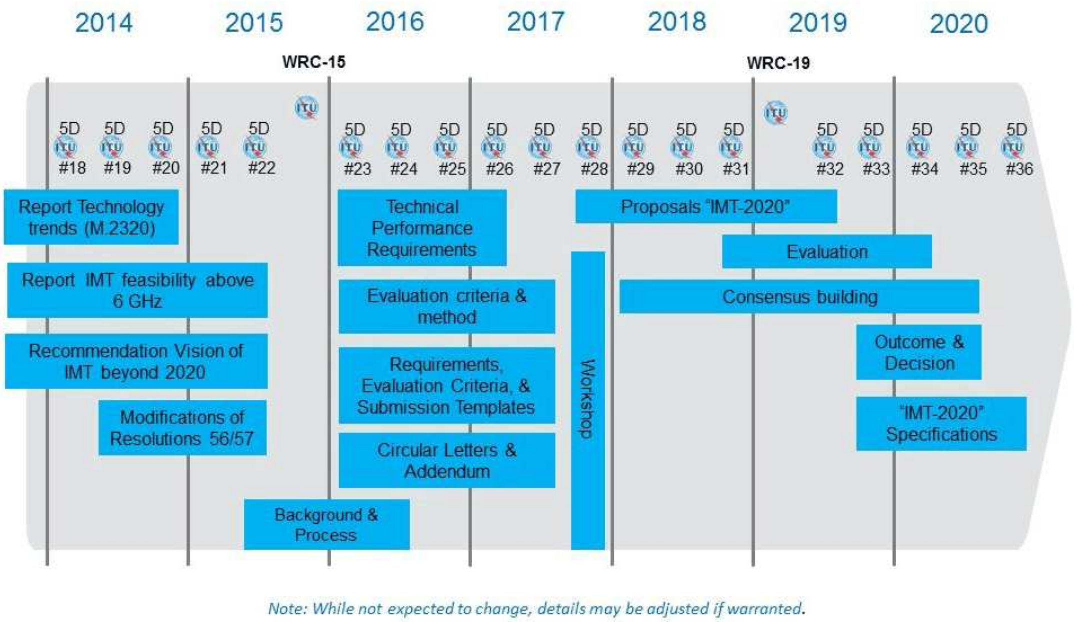
Shortly after the introduction of a new generation of mobile technology, the stakeholders, in particular the engineers, start thinking about the requirements for the next generation. In 2011 the Wireless World Research Forum published a whitepaper providing the "Requirements and vision for NG-Wireless" (Wireless World Research Forum, 2011). The

[3] In the context of LTE telephony services are provided through a fallback to 3G or 2G, so-called Circuit Switched Fallback (CSFB) until VoLTE is made available. The functionality is technically available, but is subject to investments by MNOs. (TNO, 2014a)

Next Generation Mobile Networks alliance has also developed a 5G vision, with emphasis on the business perspective of mobile operators (NGMN, 2015).

Also in 2011, the ITU-R set the stage for the development of a new set of specifications by creating Working Party 5D, facilitating regional workshops on "IMT for the Next Decade". In the course of 2015 ITU-R planned to finalise its vision on "IMT for 2020 and beyond", to be ready as input to the World Radio Conference which was held in November 2015.[4] Figure 10 provides the time line and process within ITU-R.

Figure 10: Detailed timeline and process for IMT-2020 in ITU-R, 2014-2020

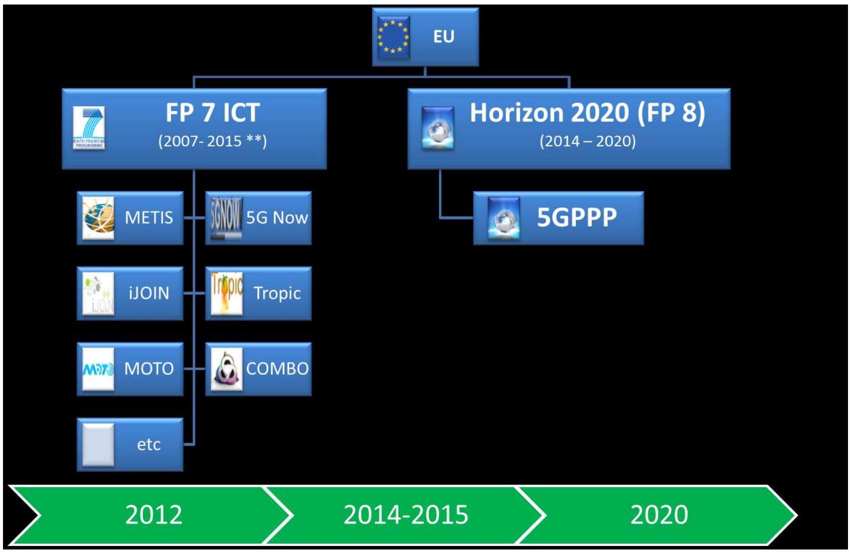


Source: ITU-R, 2015

The European communications industry, supported by the European Commission, intends to use the opportunity to regain regional leadership in the field of mobile communications and has engaged in an extensive 5G research program embedded in the European FP7 and Horizon 2020 research programs - see Figure 11.

[4] See also: http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx.

Figure 11: 5G related European research programs, 2012-2020



Source: 4G Americas, 2014a

The aim of the METIS project, which started in 2012, is the design of a 5G wireless access solution supporting:

1000 times higher overall capacity	10-100 times more devices
10 to 100 times higher end-user data rates	5 times lower latency
10 times longer battery life	

The 1000-fold capacity increase could be achieved through 3 simultaneous approaches: network densification, providing 50x improvement; the use of more spectrum, including higher frequencies, such as mmWave (e.g. 60-80 GHz), providing 10x improvement; and realising an increase in spectral efficiency, providing 2x improvement. This compares well with a doubling of aggregate network capacity every 3 years over the last 30 years (Rysavy Research, 2015).

Recognising these goals were set in the 2010-2012 time frame, and using the current growth rate, this would bring us to the year 2030, i.e. in the middle of the 5G deployment period. Hence, the capacity goal appears to be within reach.

In addition to the research initiatives, a 5G public partnership has been formed – the 5G-PPP, which brings together research institutes, operators and vendors, and was endorsed by the European Commission. A 5G Infrastructure Association was also founded and has formulated a vision on 5G including (much similar) high-level requirements (5G Infrastructure Association, 2015)[5].

The performance objectives formulated are:

[5] See for an overview of global 5G initiatives the report by 4G Americas. (2014a)

(1) radically higher wireless area capacity (1000x relative to 2010);

(2) much lower round-trip delays (latency <1 ms);

(3) very high dependability to enable (business/mission) critical applications; combined with

(4) a far lower energy consumption, to enable support of very low energy devices, such as sensors;

(5) reduced service creation time, from 90 hours to 90 minutes; and

(6) a reduction in the exposure to electromagnetic radiation.

It is foreseen that 5G implementation will be based on software-defined networking (SDN) and network function virtualisation (NFV), mobile edge computing (MEC) and fog computing (FC), in essence an architecture based on "cloud" computing, linking together a diverse set of resources for transport, routing, storage and processing, including (user) resources at the edge of the network. Moreover, it will support the development of new services through application programming interfaces (APIs) (Patel et al., 2014; 5G Infrastructure Association, 2015). See Section 6.4 for a discussion of network virtualisation.

According to the '5G Vision' statement, the 5G design is aimed at:

- bringing together the various radio access technologies (e.g. GSM, UMTS, LTE, Wi-Fi and satellite) to provide the end-users with seamless handovers;
- to provide a multitenant environment for various users groups (mobile operators, broadcasters, public safety and disaster relief, providers of cellular service for the railways); thereby
- paving the way for virtual pan-European operators, relying on national infrastructures.

The 5G infrastructure is expected to provide (virtual) network solutions for vertical markets, such as automotive, energy, food and agriculture, city management, government, healthcare, manufacturing, public transport, etc.

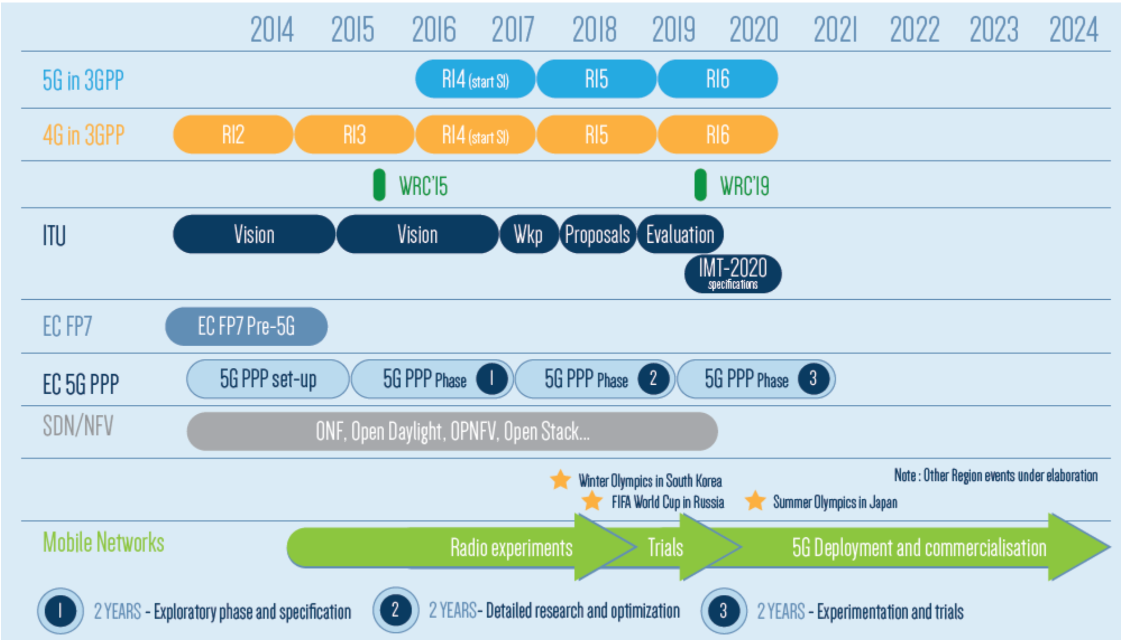
In terms of operational capabilities 5G is considered to provide (5G Infrastructure Association, 2015):

connectivity for over 20 billion human oriented terminals	connectivity for over 1 trillion IoT terminals
guaranteed user rates of over 50 Mbit/s	with aggregate service reliability better than 99.999%
communication for ground transport at speeds of 500 km/hour	an accuracy of outdoor terminal location less than 1 meter

Note that the functionality foreseen for 5G will become available over time in a series of releases of the specifications, likely as extensions to LTE –Advanced.

Figure 12 reflects the 5G roadmap in relation to the activities of the various stakeholders.

Figure 12: 5G roadmap



Source: 5G Infrastructure Association, 2015

In terms of industrial organisation, the development of 1G was an affair of national industries leading to national standards and hence a lack of interoperability. The development of 2G became regionally focused, with GSM becoming the standard adopted across Europe and beyond.[6] The development of 3G was a global standardisation effort conducted in the 3rd Generation Partnership Project (3GPP), in which ETSI was the designated European partner. 3GPP produced five releases of global standards for 3G/UMTS networks, including the IP Multimedia Subsystem and High Speed Packet Access (HSPA) (4G Americas, 2014a). It was decided that 4G standardisation would continue under 3GPP, resulting in Releases 8 through 11, while Release 12 was scheduled for 2015.[7]

This outlook suggests the creation of a unified mobile infrastructure, across a diverse asset base, which obviates the needs for dedicated wireless networks for public safety and disaster relief, for railways, and for broadcasting. It suggests that mobile network operators will act as landlords to support multiple tenants, i.e. multiple dedicated user groups with specific service requirements (with respect to reliability and availability; real time response) served through (dedicated) software defined networks. The outlook suggests, next to improved capabilities for network sharing, the implementation of APIs for service creation. It

[6] An attempt to align the 2G activities with those in the USA was made, but aborted as alignment was deemed to be too complicated. (Manninen, 2002)

[7] See: http://www.3gpp.org/specifications/67-releases.

suggests a potential diversification in asset ownership, a redefinition of the role of MNOs as Mobile Cloud Network (MCN) providers and more diversified roles for MVNOs, for instance serving industry verticals. The outlook suggests an increase in the number and variety of participating actors.

From the regulatory perspective, the outlook by the 5G-PPP assumes a continuation in the use of exclusive licenses for access to the radio frequency spectrum dedicated for mobile use, in order to ensure long-term investments into networks and access to the radio spectrum. Nonetheless, full virtualisation would imply that the frequency assets will be pooled among the owners.

It should further be noted that: "The thirst for new spectrum will likely prevail [over growing the infrastructure with smaller cells] since spectrum has an appreciating value while infrastructure is always depreciating." (Wireless World Research Forum, 2011).

Moreover, coordination in band usage remains essential for device manufacturers to make handsets available in a timely manner. Differences between infrastructure roll-out and uptake can in part be explained by the lack of devices. A typical case was the iPhone initially not supporting operation in the 800 MHz band for LTE (TNO, 2014a).

The question for the 2025 scenario is whether the raw capabilities provided by engineers will be deployed by network operators. This is very likely the case because mobile data rates are still trailing those provided on fixed networks. Moreover, in mobile networks the raw capacity, as it translates to cell site capacity, is shared among multiple users. Even if demand growth would flatten, the ability to share a higher capacity cell site would lead to a reduction of costs and therefore be pursued by mobile operators.

6.2 Convergence of CT and IT

Considering the visions for 5G, one may conclude that the visions represent the final step in the convergence of communication technologies with information technologies: mobile communication becoming 'just another' cloud application.

It also represents the next and ultimate step in the sharing of resources: from passive sharing, through active sharing to full virtualisation.

As such, the 5G vision conjures the image of a 'virtual utility'.

6.3 M2M and IoT

The next step in the evolution of the Internet is the interconnection of uniquely identifiable embedded computing-like devices using the Internet, denoted as the Internet of Things (IoT). IoT requires transition to IPv6, which has a much larger address space of up to 3.4×10^{38}, as well as low data rates with very low energy consumption.

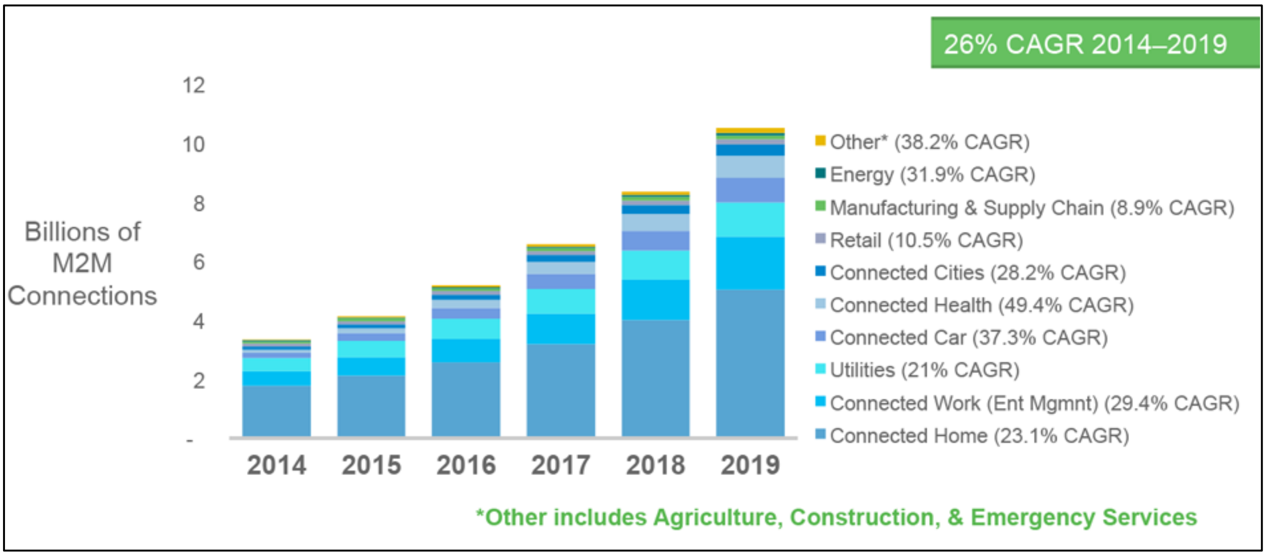
IoT includes the earlier form of machine-to-machine (M2M) communication, which originated in the field of industrial instrumentation. The ubiquitous use of the Internet facilitates M2M communication and expands its range of applications. Previously, this was also denoted as telematics. Meanwhile, many mobile operators have created departments dedicated to providing M2M services. A number of energy utility companies have outsourced the collection of smart-meter data to communication providers. One of them has acquired a radio spectrum license to set up a network to collect metering data over the air.

The lowest-cost devices enabling M2M communications today are GPRS modems, which may become obsolete as operators sunset their GSM systems. HSPA is also used for M2M communications. LTE has been optimised to efficiently communicate small bursts of information, making it well suited for M2M. Low-cost LTE modem options in 3GPP releases 10 through 13, when implemented, will reduce costs, improve the communications range, and will extend battery life (Rysavy Research, 2015).

In other instances, developers will use local-area networking technologies, such as Wi-Fi, Bluetooth Low Energy, and ZigBee. New wide-area wireless technologies emerging specifically to support IoT include: LoRa, Sigfox, OnRamp Wireless, and Weightless. Cloud-based support platforms and standardised interfaces will also facilitate the development and deployment of IoT applications. For example, the GSM Association (GSMA) is developing the OneM2M Service Layer that can be embedded in hardware and software to simplify communications with application servers (Rysavy Research, 2015).

IoT is considered to include a very wide range of applications such as: environmental monitoring; energy management; remote health monitoring and notification; building and home automation; smart vehicles; and more. According to Cisco´s VNI projection, M2M connections will grow to over 10 billion worldwide by 2019, with 4.6 Petabytes of traffic per month. See Figure 13 for the growth rates and a breakdown by industry vertical.

Figure 13: Forecast global M2M connections by industry vertical, 2014-2019



Source: Cisco, 2015

In terms of industrial organisation, the Internet-of-Things is expected to encode 50 to 100 trillion objects globally and to be able to follow these objects. Human beings in urban environments are expected to be individually surrounded by 1000–5000 traceable objects. This raises new issues around privacy and security, as well as of autonomy and control (Höller et al., 2014).

6.4 Network virtualisation

Network virtualisation refers to implementing the functions of the communications infrastructure in software running on commercial 'off-the-shelf' computing equipment.[8]

AT&T describes the motivation to move towards network function virtualisation (NFV) as follows: "AT&T's network is comprised of a large and increasing variety of proprietary hardware appliances. To launch a new network service often requires adding yet another variety, and finding the space and power to accommodate these boxes is becoming increasingly difficult. This difficulty is compounded by increasing costs of energy, capital investment, and rarity of skills necessary to design, integrate and operate increasingly complex hardware-based appliances. Moreover, hardware-based appliances rapidly reach end-of-life, requiring much of the procure-design-integrate-deploy cycle to be repeated with little or no revenue benefit. Additionally, hardware lifecycles are becoming shorter as technology and service innovation accelerates, and this can inhibit the expeditious roll out of new revenue earning network services and constrain innovation in an increasingly network-centric connected world. NFV aims to address these problems by evolving standard IT virtualisation technology to consolidate many network equipment types onto industry standard high volume servers, switches and storage that can be located in data centers, network PoPs or on customer premises. This involves the implementation of network functions in software, called Virtual Network Functions (VNFs), that can run on a range of general purpose hardware, and that can be moved to, or instantiated in, various locations in the network as required, without the need for installation of new equipment." (AT&T, 2013).

The approach promises lower capital expenditures, benefiting from economies of scale in the IT industry; lower operating costs; faster deployment of new services; energy savings; and improved network efficiency. With NFV, multiple tenants will be able to share the same infrastructure, facilitating, for example, mobile virtual network operator (MVNO) arrangements.

Network virtualisation is directly linked with the development towards Software Defined Networks (SDNs), as an architectural framework for creating intelligent networks that are programmable, application aware, and more open. SDN allows the network to transform into a more effective business enabler. SDN enables applications to request and manipulate services provided by the network and allows the network to expose the network state back

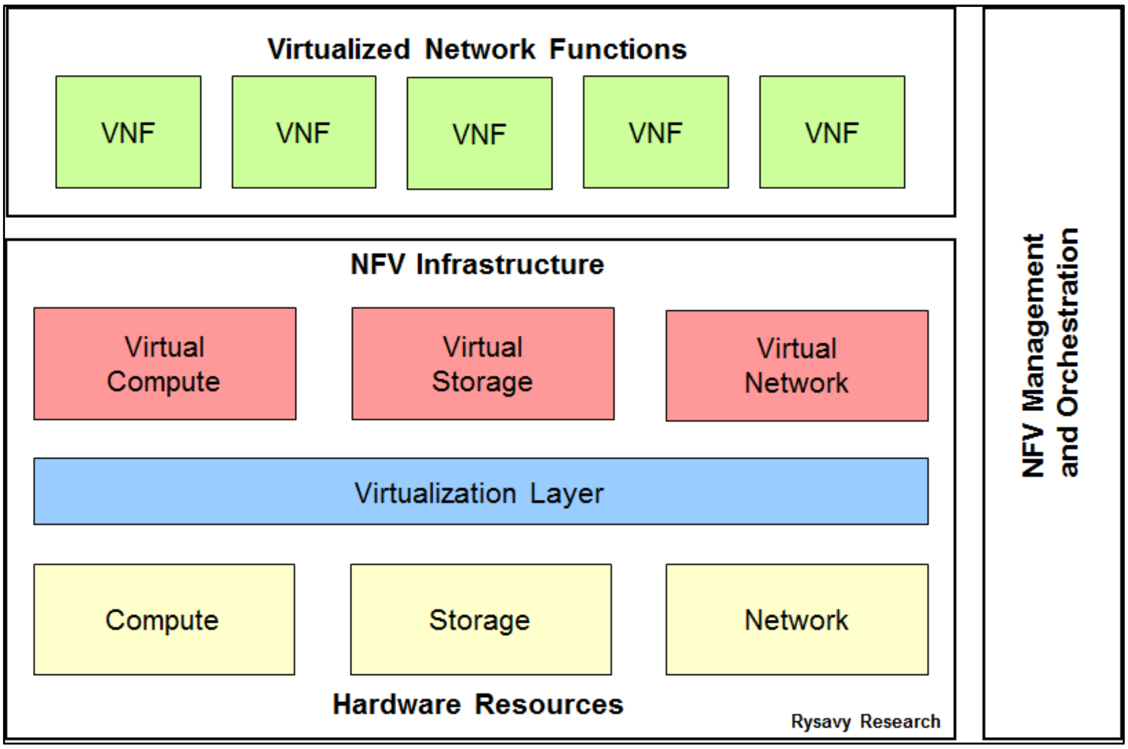
[8] See for small scale application and experimentation with virtual networks for instance the PhD by Strijkers. (2014)

to the applications. A key aspect of the architectural framework is the separation of the forwarding plane from the control plane, and the establishment of standard protocols and abstractions between the two. SDN can act as an enabler for NFV, since the separation of the control and data planes enables the virtualisation of the separated control plane software. NFV can also act as an enabler for SDN, since the separation between data plane and control plane implementations is simplified when one or both of them are implemented in software running on top of standard hardware (AT&T, 2013).

The European Telecommunications Standards Institute (ETSI) is standardising a framework, including interfaces and reference architectures for virtualisation. See Figure 14 showing the ETSI framework, in which virtualised network functions (VNFs) are the nodes or applications by which operators build services (4G Americas, 2014b). Other standards and industry groups involved include 3GPP, The Open Network Foundation, OpenStack, Open Daylight, and OPNFV. It should be noted that to date 3GPP specifications do not yet incorporate NFV.

Both the core network and the radio-access network can be virtualised. The core network, consisting of fewer nodes, is an easier starting point. Virtualising the RAN, although more complex, could eventually provide the greatest network efficiency gains, particularly for small-cell deployments (Rysavy Research, 2015).

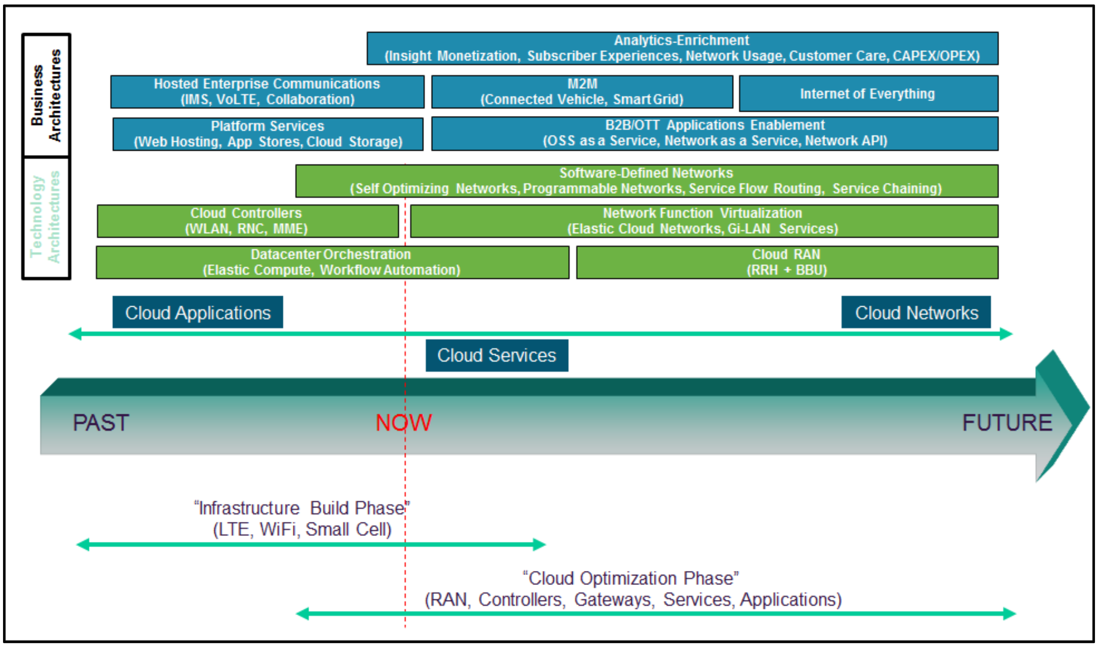
Figure 14: ETSI ISG network virtualisation framework



Source: 4G Americas, 2014b

NFV constitutes an entirely new way of building and managing networks and will take many years to mature given the complexity of the systems and their stringent performance requirements. Because of higher investment demands, RAN virtualisation is expected to emerge over a longer timeframe than core network virtualisation, and will likely occur selectively for small-cell deployments. See also Figure 15. (Rysavy Research, 2015).

Figure 15: The implementation of software-defined networking and cloud architectures



Source: Rysavy Research, 2015

It should be noted that the pooling of baseband processing in a cloud-RAN can, but does not necessarily, use virtualisation techniques. Separating the radio function from baseband processing typically requires transporting digitised radio signals across high data rate (multi-Gbit/s) fibre connections. This is sometimes referred to as front-hauling.

The introduction of NFV also implies a different role for standardisation. As phrased by AT&T: "Traditionally, carriers interested in a new architecture would gather with their suppliers and start a new standardisation activity in one or several SDOs, often calling the work Next Generation Network or NGN. The standards body would gather requirements from interested parties, work out backwards compatibility, and negotiate an outcome that was mutually acceptable and described the end-to-end system as an optimised and tightly coupled whole. This process was [is] lengthy and expensive, diminished a carrier's ability to navigate their own technology transitions, and often created entities that fail to serve the interests of the companies that fund them. This is not to say that standardisation is no longer valuable, but rather that the goals of standards activities are better targeted toward smaller, re-usable components that can be composed and recomposed into various systems and architectures." (AT&T, 2013).

The future mobile services industry is expected to include many more actors in a variety of roles with a large and diversified asset ownership structure. This implies a high dependency on private contracting, much more intricate than the current MNO-MVNO arrangements. An open question is whether entrants will be able to fully exploit the degrees of freedom offered by the software-driven API-enabled infrastructure.

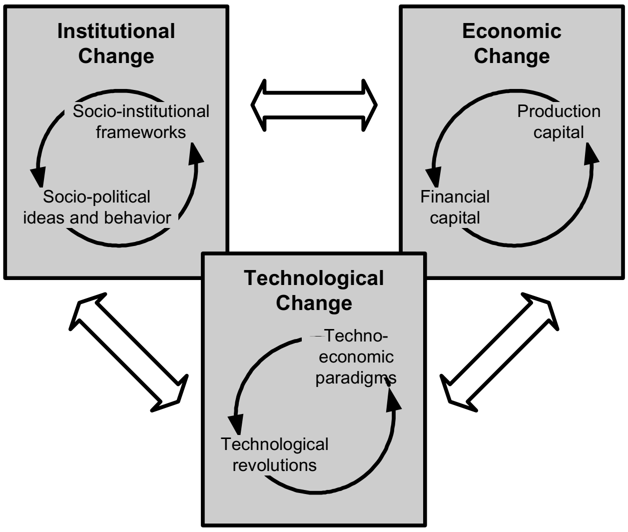
Regarding the quality assurance of the future electronic communication network, in particular in the light of its use by public safety and disaster relief organisations, the question of which industry model will prevail is of interest: the more open Google-model, the more closed Apple-model or the stakeholder model of the Wi-Fi alliance.

The diversified asset base also raises the question of investment incentives. Given the reliance on the current model of radio-spectrum auctions, a two tier model may emerge, with mobile cloud network providers investing in the base infrastructure and mobile service providers investing in applications servers. It will be of interest to assess to what degree this model will be prone to free rider behaviour or hold-up.

7. Changes in the industrial organisation of the sector

The core input of the current TEP, the microelectronic chips, transformed both the IT and the CT industries and is subsequently transforming the economy at large. As Perez pointed out, three spheres of change can be distinguished which are in constant reciprocal action: the technological, institutional and economic sphere - see Figure 16 (Perez, 2002 p156).

Figure 16: Three spheres of change in constant reciprocal action



Source: Perez, 2002.

From the early 1970s computer related communications led to a gradual erosion of the telecommunications monopolies in the USA (Melody, 1999). In Europe, the liberalisation era started with the 1987 European Commission Green Paper on telecommunications. (EC, 1987) January 1st 1998 became the date at which all remaining restrictions on service competition were to be lifted.

This fundamental shift in the industrial organisation of the telecom sector represents one of the most important institutional changes of the ICT-driven techno-economic paradigm. This institutional change, the related privatisation of the incumbents, their need to expand the business beyond the traditional business boundaries, and the Internet being opened up to the public at large, combined to fuel the euphoric period of the late 1990s – the period of 'frenzy' in Figure 1.

The liberalisation also led to the creation of new institutions, the national regulatory authorities, which became responsible for the oversight of the sector. Moreover, they became responsible for the introduction of access regulation, as a means to pry open the incumbent telephone network for competition, and for arranging auctions for the award of licenses to the use of radio frequency spectrum, e.g. for mobile communications.

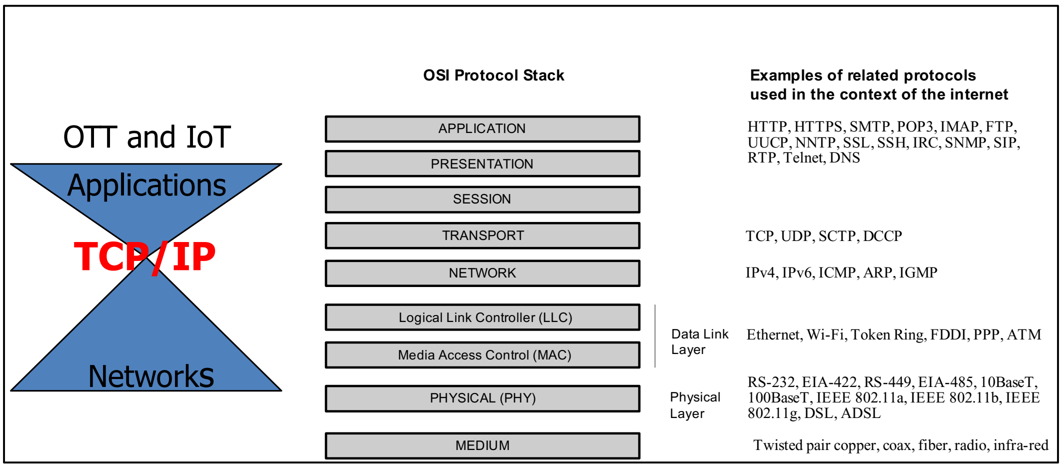
While in the previous era the realisation of public interests was realised largely along the lines of managerial control of the fully integrated telecom firm, today the realisation requires an alignment between public objectives and private firm objectives (Anker, 2013; Anker & Lemstra, 2013).

The period of liberalisation and the introduction of competition has now come to an end, the objectives largely being realised. With the start of the Junker Commission, the regulatory regime has become the subject of a major evaluation at the European level. Examples are the REFIT exercise, the study tendered by DG Competition into the role of competition on market outcomes and the impact assessment accompanying the review of the regulatory framework for e-communications by DG CONNECT. The aim is to align regulation towards the new objectives of completing the Digital Single Market (DSM) and towards more investment in communications infrastructures to enable the development of the DSM.

7.1 Decoupling of services and applications from the underlying infrastructures

The transformation to 'all things digital' and the introduction of the TCP/IP protocol stack as the core of the Internet has led to a decoupling of the services and applications from the underlying infrastructures.[9, 10] See Figure 17 for an illusatrion of this.

Figure 17: Decoupling of services and applications from the underlying infrastructures



Source: Author's own work

[9] Note that increasingly User Datagram Protocol (UDP) is used for video transmission, to improve real-time performance by foregoing the retransmission of packets received in error implied in the TCP protocol.
[10] Note that the development towards managed services, whereby functionality of the network layer is used at the application layer, is affecting this notion of effective decoupling.

This has enabled the emergence of so-called Over-the-Top (OTT) services, such as Voice-over-IP (VoIP) and TV-over-IP (IPTV) in competition with the traditional telephony and broadcasting services. Following the transition to All-IP infrastructures, these traditional services are now also being delivered using TCP/IP protocols, but using dedicated channels on the access networks.

In terms of industrial organisation, it implies that the circuit-switched paradigm is being subsumed by the packet-switched paradigm, not only in terms of technologies but also in terms of the related institutions. It implies the ITU losing its central role in the governance of the sector, being replaced by the institutions that evolved with the emergence of the Internet, such as the IETF, ICANN, etc. (Mueller, 2002, 2010; Mueller & Lemstra, 2011).

7.2 Level playing field

Whether there is a level playing field between 'new' and 'old' providers of (e.g. telephony) services is the subject of current studies, for instance through the study on "Future trends and business models in communication services" commissioned by DG CONNECT. The major issue is that the firms are subject to different rules and regulations, impacting their business models and the degrees of freedom to innovate differently.

7.3 Digital convergence: the end of dedicated networks

The transformation to 'all things digital' and the introduction of the TCP/IP protocol stack as the core of the Internet implies the end of dedicated networks, i.e. networks that have been optimised for the provision of a particular service, e.g. telephony (the public switched telephone network – PSTN) and the network for the distribution of radio and TV signals (the CATV-cable network). The PSTN network is now used by the incumbents to provide access to the Internet and to distribute RTV-programs, while the CATV-network is now also used for providing telephony and access to the Internet. This has enabled infrastructure-based competition. PSTN-based and CATV-based firms are now competing in the market for multi-play offerings, whereby access to exclusive content is used as a competitive weapon. The ability to provide mobile access to the bundle adds another dimension to this competitive game, whereby PSTN incumbents tend to have a better starting position as they typically also run a mobile network.

7.4 Convergence between broadcasting and mobile

Moreover, with increasing use of streaming, e.g. by Netflix, and on-demand viewing, e.g. for delay-TV, communications and broadcasting are converging further at the services level. To provide a more viable way to deliver broadcasting services over mobile networks, 3GPP has standardised multicast and broadcast techniques for application in LTE networks under the acronym eMBMS (evolved Multimedia Broadcast Multicast Service). Single-frequency network (SFN) technology is used to distribute broadcast streams into well-defined areas –

where all contributing cells send the same data during exactly the same radio time slots. Depending on content popularity, operators can also deliver content when network load is low, using the local cache of a user's device. This may include software upgrades over-the-air of mobile devices or one-to-many file transfer in the context of M2M/IoT.

First demonstrations were given at the Mobile World Congress in 2013 and by KPN in collaboration with Ericsson, Qualcomm, Samsung and IBM in the Amsterdam Arena football stadium, the Netherlands, in 2014. KT launched the first public LTE broadcast service in dedicated areas of Seoul in 2014 (Lohmar, Slssingar, Kenehan & Puustinen, 2013; TNO, 2014a, 2014b).

However, at this time, terrestrial digital broadcasting (DVB-T) demand is still high in Southern Europe, with market shares above 75%. On the other hand, in some Northern European countries it has dropped to less than 25%. (TNO, 2014a) A recent EBU study concluded that delivery of free-to-air broadcast content over the current DTT networks using DVB-T is at present considered more cost effective, albeit, no LTE cost calculations were made due to the 'lack of sufficient available evidence' (EBU, 2014).

In terms of industrial organisation, this development will bring broadcasters and mobile network operators into the same market. What we can observe is that a once highly efficient form of broadcasting is becoming increasingly less efficient as the number of users declines. At the same time, a highly efficient unicast system becomes less efficient as more and more users are requesting the same content at approximately the same moment in time.

Moreover, when the broadcasting viewers are divided over many different programs and are offered regional variants, the high-tower-high-power model of terrestrial broadcasting becomes less efficient and the low-power-low-tower solution applied in LTE becomes more attractive.

As the underlying trends of 'all things digital' and 'all things packet' progresses towards the year 2025, and broadcast/multicast has become a common attribute of the (mobile) Internet, one should ask the question whether and why a distinction needs to be made from an infrastructure perspective. As a consequence, the radiofrequency spectrum could be applied for 'universal' access provisioning, rather than being dedicated for a particular use, thus making the overall usage of the radio spectrum potentially more efficient.

7.5 Convergence between fixed and mobile

While fixed networks are providing higher data rates than mobile networks, end-users tend to prefer mobile connectivity for reasons of convenience, i.e. the freedom that mobility provides and the additional functionality offered by the mobile devices. In the perception of the end-users the differences at the services level will become blurred further as mobile data rates increase, latency is reduced and device screens reach higher quality levels. This is all part of the vision for the next generation of mobility, i.e. 5G, scheduled for introduction into the market by 2020. See Section 6.1.

Part of the LTE architecture is the IP multi-media subsystem (IMS). It is intended to offer access to core services and applications across multiple-access networks. IMS allows for creative blending of different types of communications and information, including voice, video, instant messaging (IM), presence information, location, and documents. For example, during a voice call, a user could add a simultaneous video connection, or start transferring files.

IMS does not provide services by itself, but represents a framework of application servers, subscriber databases and gateways to enable the provision of services. The core networking protocol used for interworking with IMS is the Session Initiation Protocol (SIP). Although IMS adoption by cellular operators was initially slow, deployment is accelerating as operators make packet voice service available for LTE (Rysavy Research, 2015).

In terms of industrial organisation, it remains an open question whether the creation of value in the network by MNOs will be preferred by end-users over value creation by third parties at the edge of the network. See e.g. Patel et al. on mobile edge computing (2014). In an earlier period of industry development a similar battle between AT&T and IBM over the location of intelligence, either in the network or at the edge, was clearly won by the IBM camp. The current developments of the Internet and OTT services and applications point in the same direction.

Nonetheless, IMS will play a central role in providing public safety services. See section 0. Moreover, open access to network functionality for third party development is foreseen in the vision for 5G. See Section 6.1.

7.6 Convergence toward next generation points of presence

Ironically, increasing mobile network capacity requires increasing fixed network capacity. As the capacity of cell sites increases to provide end-users with higher data rates, these cell sites will need optical connections to the backbone network. To increase capacity for simultaneous use by end-users requires cell coverage areas to be made smaller, hence more cell sites need to be connected, requiring a finer optical network grid. This suggests further synergies in the roll-out of fibre in the access networks. The EU FP7 research project COMBO refers to Next Generation Points of Presence, aimed at a "better distribution of all essential functions, equipment and infrastructures of convergent networks."[11]

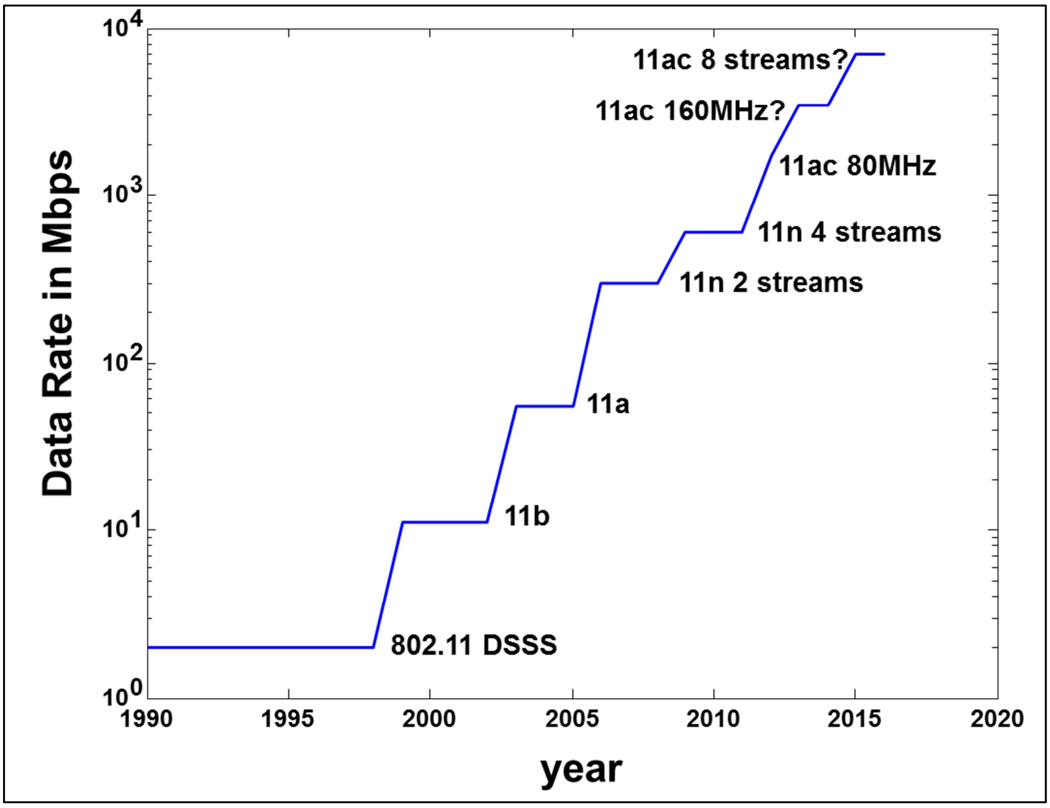
7.7 Convergence of mobile and Wi-Fi

License-exempt use of the radio spectrum is becoming ever more important to mobile broadband networks. While the initial use was a rudimentary offload onto Wi-Fi networks, Wi-Fi networks are gradually becoming more tightly integrated into cellular networks.

[11] See : www.ict-combo.eu.

Unlicensed spectrum is mostly used for short range devices, resulting in high-frequency reuse and much higher throughput rates per square meter of coverage versus typical cellular deployments. The IEEE 802.11 family of technologies has experienced rapid growth, mainly in private deployments – residential and business – and by operators in hotspots, hotzones and in homespots. The latest 802.11 standard, 802.11ac, offers peak theoretical throughputs in excess of 1 Gbps and improved range through use of higher-order MIMO. See Figure 18 showing the outlook for 2020.

Figure 18: IEEE 802.11 data rate growth, 1990-2020



Source: Van Nee, 2012

Another approach for using unlicensed spectrum employs LTE as the radio technology, initially in a version referred to as LTE-Unlicensed (LTE-U), which will work with Releases 10-12 of LTE. In Release 13, 3GPP is specifying License-Assisted Access (LAA), which implements listen-before-talk capability, a requirement for unlicensed operation in Europe. Initially, carrier aggregation combines a licensed carrier with an unlicensed 20 MHz carrier in the 5 GHz band as a supplemental channel. Operating LTE in unlicensed bands could decrease the need for handoffs to Wi-Fi. LTE uses spectrum efficiently under heavy load thanks to its more centralised over-the-air scheduling algorithms. An alternative approach for integrating Wi-Fi is called LTE Wi-Fi Aggregation (LWA). LTE handles the control plane, but connections occur over separate LTE base stations and Wi-Fi access points. To support this, LWA devices need a software upgrade (Rysavy Research, 2015).

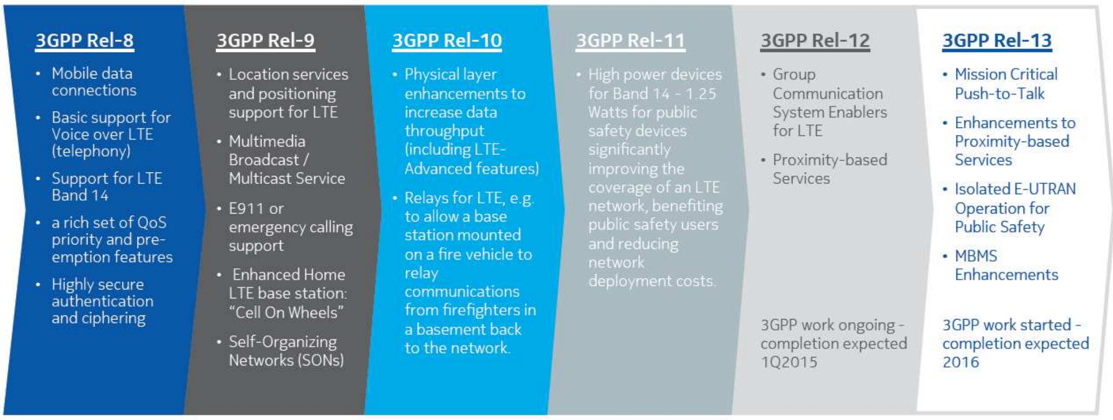
From an industrial organisation perspective, a (major) concern with using LTE in unlicensed bands is whether LTE will be a fair neighbour to Wi-Fi users.

For additional discussion, see Section 6.1 on the convergence of IT and CT as it is taking shape in the next generation of mobile technology – 5G.

7.8 Convergence between mobile and public safety networks

The specific needs of public safety and disaster relief organisations has led to the development of dedicated networks for mission-critical voice services and narrowband data. In Europe this is the TETRA (Terrestrial Trunked Radio) network. The evolving needs of the users, e.g. for broadband data and video, cannot be provided by these networks. A solution is the use of LTE, which can readily provide broadband data and is scheduled to provide mission-critical voice in an upcoming release - see Figure 19 (Nokia, 2014).

Figure 19: 3GPP release schedule for public safety



Source: Nokia, 2014

There are two principle options: (1) a dedicated LTE network providing for public safety and disaster relief; and (2) commercial LTE network providing for these services. Option (1) gives the benefit of economics of scale in the use of LTE equipment, but requires its own infrastructure and access to the radio frequency spectrum. This option has been chosen by the US authorities and is scheduled for deployment in 2017-2018. Option (2) allows the full sharing of the network and spectrum access between public safety and commercial users. Albeit, public safety users will have priority access and a set of special features. This option has been chosen by the UK authorities. The way the sharing is to be implemented remains to be decided (Nokia, 2014; Rysavy Research, 2015).

In terms of industry structure, the UK scenario implies a change in the governance of public safety communications, from being implemented through a set-aside of radio spectrum by the National Regulatory Agency and a public sector contract for the implementation and exploitation of a dedicated network to a contract for service delivery negotiated with one or more MNOs. It further implies the release of the spectrum dedicated to TETRA for general

LTE use. The shared solution suggests an optimal use of resources, in particular of scarce radio spectrum.

In terms of regulation, the end of dedicated networks implies that technology specific solutions for the implementation of particular services of public interest, such as access to emergency services, or the notion of universal service, will need to be redefined, to become technology-neutral in their specification.

8. Robustness of the 2025 image

The image of the electronic communications industry for 2025 as developed in this contribution has largely been grounded on observed regularities and trends. Nonetheless, discontinuities or set-backs may happen and they will affect the image. In the following section we will review the end of the current TEP and the beginning of the next. Subsequently, a reflection on innovations over the past ten years is provided as a way to make us aware what might happen in terms of innovation in the next 10 years. In the final section the use of scenarios by Shell as a means of testing the robustness of firm strategies is discussed, suggesting the same approach may be applied for testing the robustness of policy and regulation.

8.1 Diffusion of the ICT-driven techno-economic paradigm

The succession of technological revolutions, caused by a clustering of innovations, occurs every 50-60 years. The image of the year 2025 is positioned in the second half of the diffusion period of the current ICT-driven techno-economic paradigm. By that time the paradigm will have been broadly established and the first signs of the next technological revolution should be visible. Making a statement on the likely next revolution is speculative, but it may well be centred around bio-informatics and bio-synthetics. The installation period may begin around that time, but the period of frenzy, the major shift, will likely be a number of years into the future.

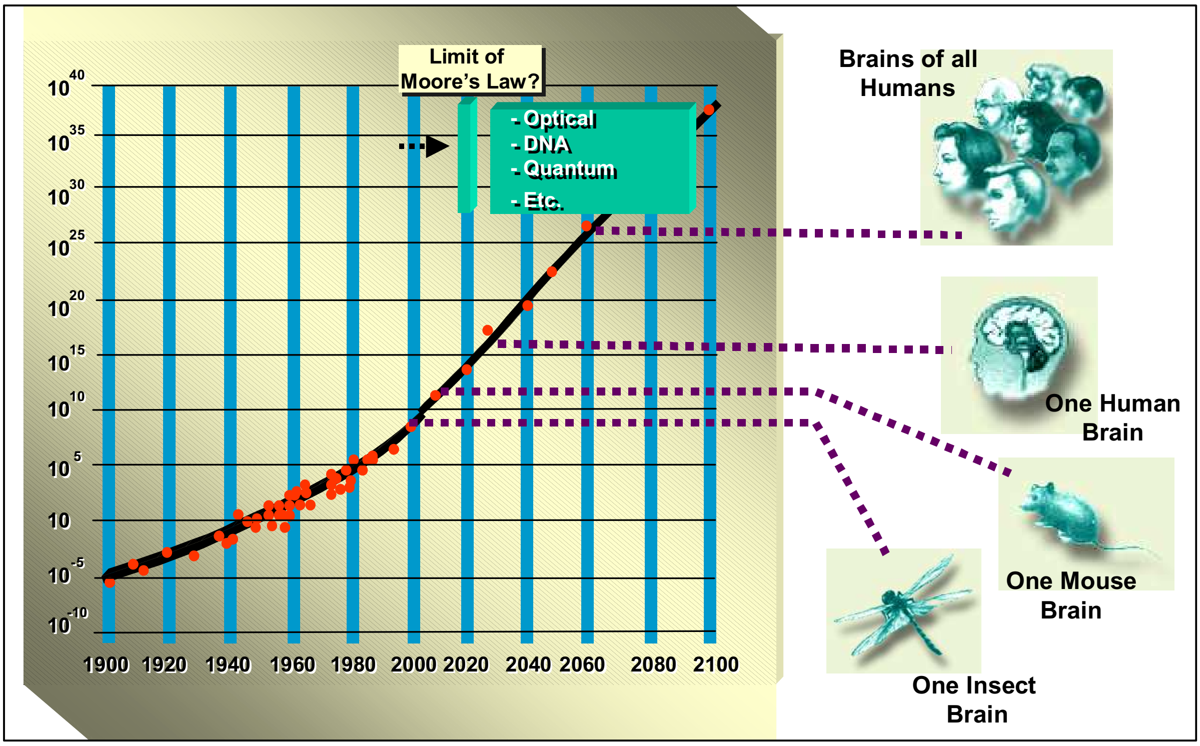
While the core inputs in earlier technological revolutions were in essence substitutes in terms of inputs, e.g. steam-power replacing water-power, followed by electricity replacing steam, the input of the current technological revolution is additive, i.e., information transport and processing is enabled by electricity. In the next revolution, the ICTs are also expected to continue as a major input, the electronic communication infrastructure as a major carrier.

8.1.1 Moore's Law

2015 marks 50 years of Moore's Law (Mack, 2011; Golio, 2015; Mack, 2015). There is a physical limit in terms of device scaling of silicon, but as Moore's Law also captures engineering prowess in mastering the related physics and economics, it may extend well beyond 2025, as alternative technologies and alternative computing techniques are explored, such as quantum computing. Figure 20 provides an illustration of progress in computing (number of calculations per second on the y-axis at $1,000) as compared to brain capacity (based on: Kurzweil, 1999 p104; 2005).

What may be expected is a slowdown in the progression as predicted, affecting the high-end computer and communications applications. On the other hand many applications that come under the header of IoT do not require higher data rates, but lower rates and more energy efficient use of the communications protocol.

Figure 20: Exponential growth of computing, 1900-2100

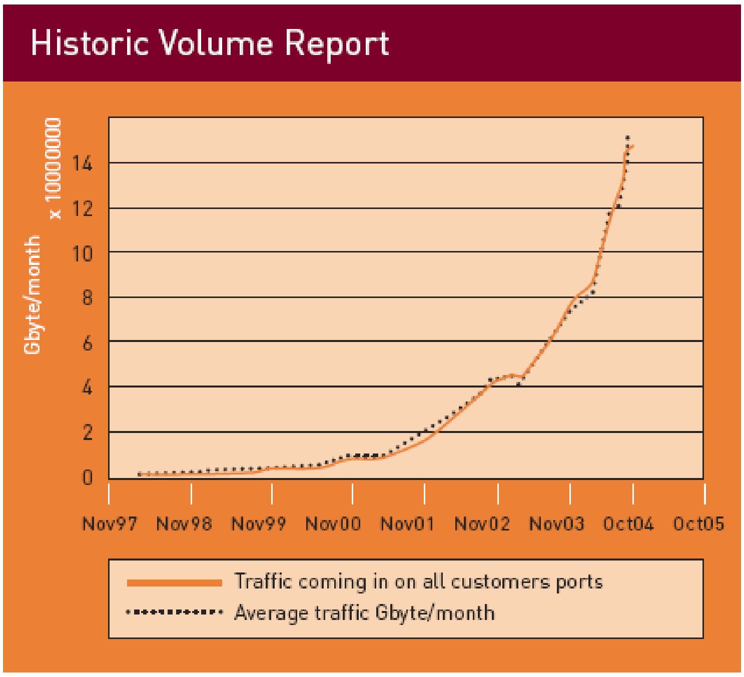


Source: Kurzweil, 1999; 2005

8.1.2 Growth trends

The end of the euphoric period at the turn of the century was followed by a collapse of the telecom industry. The turnover of firms on the equipment supply side dropped with 30-50%. The introduction of 3G was delayed. While the Internet growth rate declined, it remained positive, as measured at the Amsterdam Internet Exchange - see Figure 21 (Ams*ix*, 2005). As euphoric periods and subsequent setbacks are recurring economic phenomena, we may expect other periods of slow-down as we move towards 2025.

Figure 21: AMSIX volume report, 1997-2005



Source: Amsix, 2005

8.1.3 Trust and privacy – cybercrime and big data

As Information Rules do not discriminate between legal and illegal businesses, with lower transaction costs, the use of malware and cybercrime has proliferated. This affects the confidence of users and affects the uptake of electronically mediated business. Furthermore, the capabilities of big data analysis represents a serious threat to privacy and confidentiality in the use of the Internet. Large scale commercial exploitation of profiling data could lead to a backlash, potentially suppressing the use of the Internet.

8.2 The role of innovation: past, present and future

So far our perspective on the 2025 scenario has been informed by observed regularities and trends. Hence, this perspective primarily reflects innovations of the past. Innovations in the future are hard to predict. However, having an understanding of the innovations which have occurred in the past 10 years will provide a sense of what might be happening in the next 10 years. Figure 22 below captures the innovation over the past 10 years as related to major events in the Internet, computing, telecommunications and media industries. Some important social media events (such as the introduction of Facebook in 2004) are also included in the list. To obtain a sense of broadband developments, the relevant milestones in fixed and mobile broadband in The Netherlands are also included (viz. BBned, KPN, T-Mobile, Versatel and Vodafone entries). The list is illustrative and not intended to be exhaustive.

The past 10 years were characterised by three main phenomena, essentially from their start to broad adoption: (1) broadband – fixed and mobile; (2) social media – Facebook, Twitter and YouTube; and (3) the smartphone ecosystem – exemplified by the creation of the Apple ecosystem with the iPhone, iPad, the App-store and iCloud. In this period we also see the development of 4k TV, but this development takes place much more in the background.

The period sees a further consolidation of the telecom equipment providers and a shift toward Internet related companies leading innovation – see the right-hand column of Figure 22 for some major events.

Figure 22: Major Internet, computing, telecom and media events, 2004-2015

Date	Internet event	Computing event	Telecom/Media event
2004	Google acquires Keyhole, to become GoogleEarth	DARPA Grand Challenge: Driverless car challenge in the Nevada desert	Versatel introduces ADSL2/2+
	Facebook founded		Sony introduces 4k TV projectors
	Flickr established		First 3G commercial service in NL by Vodafone
	Hyves introduced		
2005	eBay acquires Skype for $2,6 bln		SBC acquires AT&T and changes name to AT&T
	YouTube founded by Hurley, Chen and Karim		Verizon acquires MCI
			Alcatel and Lucent Technologies merger announced
			KPN introduces VDSL from street cabinet
2006	Twitter introduced	Moore's Law: Entering second half of the chess board	FCC approves AT&T Bellsouth merger
	Google acquires YouTube for $1,65 bln	Sony introduces PlayStation 3 with 1,8 teraflops	Ericsson acquires Marconi assests
	YouTube agreement with MGM, CBS and others for posting full length films and TV episodes	ASCI Red super computer decommissioned	Nokia and Siemens announce 50-50 joint venture Nokia Siemens Networks
			T-Mobile provides first HSDPA in NL
			DOCSIS 3.0 specification released
2007	Netflix introduces streaming movies	Waze founded by Levine and Shinar, navigation system using real time data from smartphones	BBNed introduces VDSL2 (CO) (max 50/10; majority 40/8)
	Google acquires DoubleClick for $3,1 bln		Launch iPhone by Apple
2008	Launch Apple App Store		Apple announces iPhone3

	Airbnb founded by two design graduates from the Rhode Island School of Design		3GPP Release 8, standard for 4G released
2009	WhatsApp founded by Acton and Koum; later in the year launch of service for iPhone		
2010	Instagram developed by Systrom and Krieger	Apple announces iPad	KPN introduces VDSL2 bonding
	Whatsapp for Android OS launched	Google announces autonomous car with LIDAR sensing by Velodyne	NL government auctions 2.6 GHz band, Tele2 and Ziggo/UPC new entrants
	Viber launched by Marco, Magazinnik, Maroli & Smocha	Microsoft launches Kinect sensing device for Xbox	
	YouTube supports 4k video		
2011	Microsoft acquires Skype from eBay for $1,9 bln	Lionbridge and IBM partnership offers Geofluent online instant chat translater	Apple announces iPhone 4S with Siri voice recognition
	Google+ social website introduced	IBM's Watson contestant in Jeopardy!	KPN introduces VDSL2 from street cabinet
	Google acquires Motorola Mobility for $12,5 bln	Apple introduces iPad2	
2012	Facebook acquires Instagram for US$1 bln	DARPA announces Robotics Challenge	Apple announces iPhone 5
	Facebook reaches 1 bln users	Sony introduces first 4k home theater projector	KPN introduces VDSL2 vectoring
	Facebook IPO at $104 bln		NL govt multiband auction
2013	Apple announces iCloud		DOCSIS 3.1 specification released
	Google acquires Waze for US$1 bln		KPN introduces G. inp DSL layer retransmission
2014	Facebook acquires WhatsApp for $22 bln		Apple announces iPhone 6 and 6 Plus
	Netflix starts 4k TV streaming		G. fast specification released, includes vectoring G.993.5
	Google acquires home automation producer Nest for $3,2 bln		HIGH TV first 4k general entertainment TV channel
	YouTube introduces Music Key streaming subscription service		KPN national coverage 4G in NL
2015	YouTube supports 8k video		Verizon to buy AOL for $4,4 bln
			Nokia to acquire Alcatel-Lucent for € 15,6 bln

Source: Author's own work

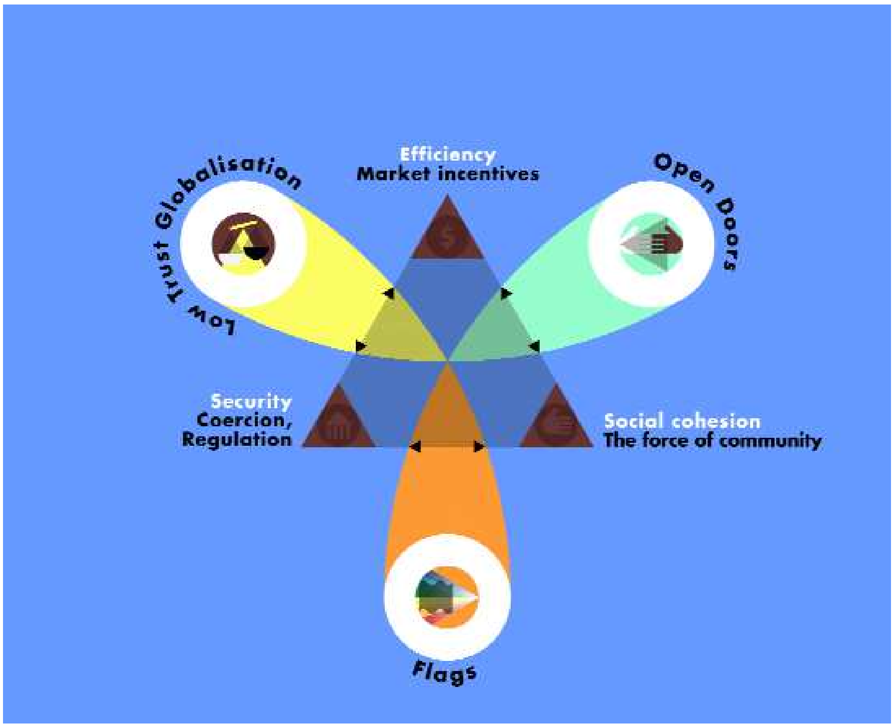
8.3 Shell scenarios

The stated aim of the scenario approach in strategic planning as applied by Shell is “to develop leaders who are better at seeing patterns of behaviour that may differ from a conventional view of the world. They also help us recognise there may be a breadth of possible outcomes to events that cannot be fully controlled, not ignored, but may be influenced... … The more clearly we see the complex dynamics of tomorrow’s world, the better we might navigate a path through the turbulence […], making wiser choices on the journey and fostering deeper partnerships.” (Shell, 2013).

Shell has a long tradition of developing scenarios of possible futures, typically orthogonal or at least of contrasting worlds (Van der Heijden, 1996; De Geus, 2002). The description of those worlds could also be used to test the robustness of government policy and regulation. The scenarios are designed to capture global developments.

The scenario for 2025 created in 2005 (and extended in 2007) presents the dual crisis of security and trust, exemplified by the 9/11 attack on the Twin Towers and the collapse of Enron. These have affected national security and trust in the market place. It brings into focus the (lack of) power of the state to regulate and coerce. These elements were added to the 2001 scenarios which already captured market incentives and the force of community. In terms of possible futures these forces lead to the triad of ‘low trust globalisation’, ‘open doors’ and ‘flags’ as tradeoffs achieved among market participants, civil society groups and states, with particular attention to the role of investors and regulators - see Figure 23 (Shell, 2005, 2007).

Figure 23: Shell global scenarios to 2025



Source: Shell, 2005, 2007.

In the 2013 scenarios a set of new lenses is provided “that can help us view familiar landscapes from fresh angles so that we can focus and clarify possible futures.” (Shell, 2013). In the scenarios, ICTs play an important role, therefore highlights are provided below. In addition, the European Union features as an example.

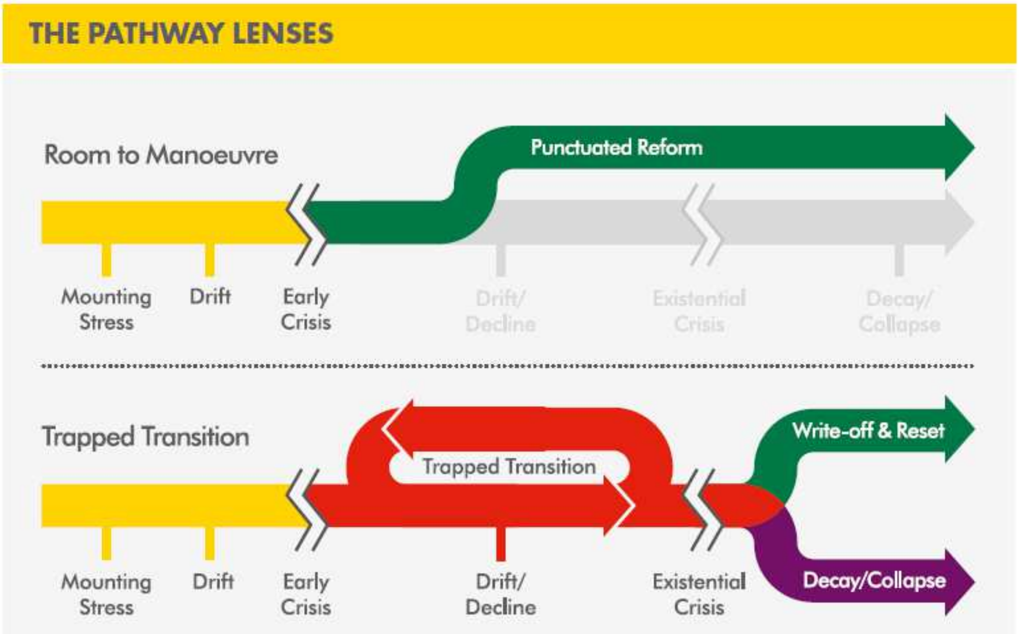
One set of lenses provides the perspective of ‘mountains’ versus ‘oceans’. ‘Mountains’ represents a world with status quo power locked-in and held tightly by the current influential. ‘Oceans’ represents a world where influence stretches far and wide. Power is devolved, competing interest are accommodated and compromise is king.

The second set of lenses is related to three paradoxes: the prosperity paradox, the connectivity paradox and the leadership paradox.

The connectivity paradox is described as follows: “Growing global connectivity stimulates creativity but also puts intellectual property at risk. Connectivity facilitates individual expression and empowerment, but also encourages herd behavior and amplifies swings in confidence and demand. The burgeoning availability of information has the capacity to bring insight and transparency, but data overload is equally likely to generate confusion and obscurity. In many ways the Connectivity Paradox drives the other two paradoxes. The deployment of information and communication technology has been a driver of economic globalisation, extending and deepening trade, financial, and research links, spreading prosperity, and generating leadership challenges. Economic, political, and social volatility may have always been with us, but this unprecedented degree of connectivity is contributing to unusual intensity in part because growth in connectivity empowers individual players. A poor street vendor can spark the toppling of governments across the Middle East, for example. A lone hacker can disrupt the functioning of large business and government enterprises. Under the banner of 'Anonymous', small numbers of 'hacktivists' can cause millions of dollars of losses to companies. A Scottish church choir singer can become a star overnight after her audition video for a TV show goes viral. And her album can become the number one best-selling album in charts around the globe."

The third set of lenses focus on 'pathways': 'Room to manoeuvre' and 'Trapped transition'. See also Figure 24 (Shell, 2013).

Figure 24: Shell scenarios: Pathway lenses



Source: Shell, 2013

Regarding the 'trapped transition' a recent example is provided: "The European Union proved not to have this level of resilience [reference is made to China and Brazil following the financial crisis], and has been following a Trapped Transition pathway in which the 'can' keeps being 'kicked down the road' while leaders struggle to create some political and social breathing space. So there is continuing drift, punctuated by a series of mini-crises, which will eventually culminate in either a reset involving the writing off of significant financial and political capital (through pooling sovereignty, for example) or the Euro unravelling."

9. Concluding remarks

While the future cannot be predicted with a high degree of certainty, creating a vision of the future opens the opportunity for a broad dialogue on which type of future is preferred. As such it provides ‘food for thought’ in developing policies – policies that can be aimed at facilitating the development in the direction of the more desirable future. Moreover, policies can be tested for their robustness under different perspectives of the future.

To stimulate the thinking and discussion on the consequences of a particular future scenario, it can be of great help if the differences with the past are articulated along various paradigm dimensions, such as in Table 2 which compares the past Fordist paradigm with the current ICT-driven techno-economic paradigm. The shifts in the operational practices when moving from hardware centric world towards a software centric world, as identified by AT&T, may serve as a good starting point. See the table below.

From	To
Hardware Centric	Software Centric
Separate IT/data center & Network/CO	Common technology & technical plant
Quarterly software releases	Continuous software process - “sandbox.”
Geographically fixed, single purpose equipment	Highly dynamic & configurable topology & roles.
Tight coupling of NE, generic, EMS & NMS/OSS	Separation of physical & logical components.
Separation of service elements & support systems	Integrated orchestration, automation & virtualisation.
Faults as service failures	Faults as capacity reduction events.
Hardware monitoring appliances	Software based monitoring.
Service specific resource combinations	Profiles, templates & reusable resource combinations.
Special design and provisioning processes	Configurable catalog/rule-driven delivery frameworks.
Optimised provider network & ops process	Optimised customer experience.
Highly constrained, independent & disaggregated control planes	Highly integrated & automated control planes driven by customer & operator policies.
Limited service dimensions	Multifaceted service dimensioning.
Highly constrained data translation & synchronisation solutions for shared management knowledge between network & systems	Shared management “Data Bus” technology between network & systems.
Slow tooling changes requiring coding	Rapid tooling changes using policies/rules
Network management	Customer experience management
Long lead provisioning times – often hardware and process constrained	Real-time provisioning
Static billing and charging	Granular and dynamic usage-based charging, billing, financial management, subscription

Source: AT&T,2013.

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