European Commission DG Research: Key Technologies Experts Group

⇒ Key Technologies For Europe: Communications

- **By** Petros KAVASSALIS, **ATLANTIS Group at University of Crete** <petros@cfp.mit.edu>

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Executive Summary

This Report examines some of the technological and organizational challenges in Communications technologies and networks, taking into account both developments currently underway and the longer term evolution of the Internet and of expanding digital networks. It gives an overview of where the EU stands (strengths – weaknesses – opportunities – threats) in this critical area for the development and prosperity of Information Society Technologies (IST) and also provides a forward look into the upcoming research challenges.

During these last years, digital networks have become a critical component for new business and social functionalities that would be totally impossible to be obtained otherwise. This is because communications technologies have migrated from the laboratories and the head offices of the telecom operators to a ubiquitous presence in production and exchange processes, delivery channels and, virtually, in any organizational structure that shapes modern economic and social life. The Internet is of course the drive of this evolution and the "engine of production" for many novel networked applications. These applications, introduced from the "edge" of the network, add diversity and increasing complexity into a very heterogeneous communications infrastructure that needs to be more efficient, robust and reliable.

Correspondingly, research in communications technologies has correspondingly moved out from the specialized laboratories of the old telecom operators and shifted orientations and methods. But long term research has been considerably "downsized" in the favor of a more "commercial" R&D strategy aiming at producing nearer-term technologies, product-related innovation and custom network solutions. However, the public Internet grows and prospers, and goes through various innovation waves to meet new requirements, thus continuously changing its structure. Simultaneously, mobile networks keep their evolutionary pace and impose as serious alternative infrastructures to legacy voice services while, together with the emerging wireless and ad hoc networks, broadening the Internet with new branches and ramifications. In brief, communications infrastructures should be now broadly-defined since they get more and more heterogeneous and complex, and need to be "evolutionary" by deploying new networking ideas that realize the potential of the "converging technologies" and by incorporating these new branches in a totally seamless way. Besides, they should allow for the emergence of effective information economies and other virtual structures supporting communities and individual social and professional lives. Do we have the right apparatus to respond to these challenges?

Many researchers and industry observers seem to recognize that in facing this complexity, we absolutely need to turn again into long-term / high impact research and define a more ambitious communications policy in this regard. But, as a recent workshop hosted by the Columbia University concludes[1], in order *"to justify the support of and the investment, a vision of the accomplishments and rationale for basic research needs to be articulated and promulgated"*. Such a vision, and this is the essential recommendation of this report, might accept that a long-term research, currently,

[1] See the Report from this Workshop, entitled "Basic Research in telecommunications", available at http://www.citi.columbia.edu/CITI_Research_advisorycomm.pdf).

should of course contribute to define a broader horizon for the innovation but it also needs to be effective in the sense of: i) recognizing priority areas (and selecting key-research problems) with high impact in evolution of the communications technologies and networks, ii) using a mix of different perspectives, ranging from pure to basic & high-level applied research and systems engineering – and maybe call for some interdisciplinary support and, finally, iii) addressing the relevant policy issues which are necessary to stimulate technology transfer from research to application.

In Europe, although long-term research in communications has somehow affected by this pressure to immediate and "commercial" results, research-supporting public structures appear to have more content and vigor than in other countries. Moreover, long-term research, in general, is imposing as a shared value among European policy-makers and citizens. The need for Europe is rather to better balance resources between market-driven / low risk and long-term / high impact / high risk research[2] and give to the second the effective organizational structure to become the sustainable "commons" for innovation. And the challenge for Europe is not exactly to "articulate and promulgate" a rationale for long-term research in communications but, in fact, to understand the evolutionary paths of these technologies and define effective long-term research priorities to "make sense" in the next phase of the evolution cycle – that will succeed to the current "turning point" period and will deploy the full potential of the "Information Age" paradigm. In fact, one of the main weaknesses of Europe, as it comes out from a SWOT analysis we have performed, is an apparently limited "absorptive learning capacity" with respect to Internet transformations. But opportunities arise today exactly from the understanding and the leverage of the potential of these transformations (that create conditions of disruptive changes and result in positions re-distribution) and from the experimentation with novel architectures and designs – especially as far as it concerns mobile communications whereas Europe enjoys a leading position.

In this document, we decided not to provide a list of critical technologies that will condition the future of the filed, or a detailed taxonomy of high potential research areas. Instead, we outline here some key areas (full of open research problems stemming from the "socio-economic complexity" of the Internet and the immense co-ordination challenges it poses) that lie at the core of the evolution of the communications technologies and networks. To do so, we deliberately opted for a short investigation of the evolution trajectory of the telecommunications industry to understand, through a portrayal of evolutionary paths, what the critical requirements of today and tomorrow are. We depicted some of them: *novel design architectures, formal network theories* and (need for) *interdisciplinary research.* During this evolutionary analysis, we appreciated also the expanding boundaries of the sector, which in the ongoing post-telecommunications era seems to embrace a large range of independent and interoperating "blocks", infrastructures, applications, services and more: digital networks that take over (localized) physical markets and physical interchanges, to connect (in a unprecedented way) systems, processes and functions within and among companies, between business and customers, and among customers, as well as between governments, citizens, educational, social and professional communities and so forth. To summarize, here are the key long-term research areas recommended by this report:

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[2] This is also one of the main recommendations of FISTERA Project (Foresight Analysis on Information Society Technologies in EU25+), see: http://fistera.jrc.es/.

1. Enabling infrastructure technologies and technologies for security
2. Applications (focusing on real time and organization-wide applications)
3. Network design and novel architectures for the Internet
4. Models for understanding the networks of today and tomorrow
5. Cyberinfrastructure, digital networks and information economies
6. The triangle Internet, Mobile, Wireless (or beyond "beyond-3G").

1. The Socio-economic Challenges for Europe in Communications

In all developed countries, Information and Communication Technologies (ICT) are considered as one of the major drivers for growth [1]. In Europe, as revealed by the Lisbon targets and the more recent i2010 strategy [2, 3], ICT have become an essential policy priority. ICT performance is largely accepted as a condition for the reinforcement of the competitiveness of the European economy and as a principal strategy for making the EU "attractive" to foreign investments, as it is recently pointed-out by Commissioner G. Verheugen. The high priority given in the Lisbon process to the growth and adjustment of the economy, in the new conditions of a more knowledge-driven economy, is also reflected by the increasing financial support to pre-competitive ICT research that is provided through successive EU framework research programs.

ICT is a vast industrial area that includes various activities and markets. According to OECD [4], the guiding principle for the delineation of ICT should lead to a definition of the sector on the basis *"of manufacturing and services industries whose products capture, transmit or display data and information electronically".* Apparently, that definition embraces activities belonging to a large pool of industries, ICT and non-ICT, from computer hardware and telecommunications equipment to software and communications services (including even IT-based consulting services). Ultimately, all of them are performed with the use of computers and communications technologies.

Communications networks, which is the specific subject this report focuses on, is the particular domain of the ICT sector encompassing those technologies that interconnect people, business and markets by moving data and information. In current days, the Internet, a complex infrastructure constituting of many heterogeneous networks and connecting billions of users, is at the center of the digital communications domain. People believe that the Internet is the engine of growth for an Information Society, where knowledge plays the primordial role in creating the "wealth of nations" and "increasing returns" drive the competition process. Many years ago, it was another communication technology, a combination of railways and telegraph networks, which revolutionized the industrial world by making possible astonishing efficiencies, obtained through the "economies of scale" generated by the "mass-production system", and introduced the modern large business firm and its complex managerial hierarchy.

But the Internet is a decentralized network that evolves from the "edge", from the decisions of the networks nodes where Internet users are located. How such a network should be operated to deliver efficient information services is a great challenge for Europe and there are in this regard enormous opportunities which have to be leveraged. Europe can build new strengths in the communications field where its position has been traditionally strong and European societies can globally benefit from better using the Internet resources. The policy challenge therefore consists in conducting anticipatory action on the grounds of:

- Realizing the potential of: i) the evolving characteristics of the Internet and the mobile networking infrastructure that de facto emerged as a real complement of the Internet, ii) the new requirements that come into sight from the applications these network support and, iii) the real potential of the expanding digital networks (digital networks lay on top of the Internet functionality to take over localized physical markets and physical interchanges, to connect in a unprecedented way systems, processes and functions within and among companies, between business and customers, and among customers, as well as between governments, citizens, educational, social and professional communities and so forth).

- Accelerating the diffusion of the Internet within the corpus of the economy and stimulating the adoption of digital networking across the European firms and public administrations.

Understanding the evolution paths of the Internet and solving, based on this understanding, novel practical problems that are introduced by decentralized networks, will contribute to realizing a powerful and flexible engineering science in Europe and to elaborating innovative business strategies that can appropriate higher value from the Information Society infrastructures. Stimulating the use of the Internet serves at improving core economic and social needs of the European society. Certainly, both issues relate to complex policy making and strategizing processes, but in both, R&D is a critical aspect. As we will explain later on, understanding in depth the evolution of Internet (more generally exploring the potential of the emerging digital networks) and providing the appropriate responses to the new requirements, essentially depends on long-term research. Such research should help the effective action of the European business firms to influence the technology futures and would facilitate the role of markets as capital providers for technology investments.

2. European Science and Technology Base in Communications

2.1. EU positioning in the sector

As already mentioned, Europe has a historical strong position in the communications sector, especially in the field of mobile technologies and networks where it maintains leadership. Traditionally, EU performs better in the sector of Communications (the C of the ITC) than in the Information Technologies (IT) sector where it still fails to catch-up with US and Asian countries. Many believe that Europe seems to have lost a part of the lead even in the telecommunications industry, where it had a net advantage in the era before the Internet, i.e., at the times of *circuit-switched* network architectures [5]. But even so, it appears that during the last 5 years, EU maintains leadership (or above average performance) in a number of critical communications technologies: 3G, antenna, cellphones and information appliances, digital cellular base stations, digital signal processing and mobile processing, Grid networking, Power Line based transmission, radio connectivity, Wi-Fi technologies and software radio. This is at least the conclusion of a recent and exhaustive FISTERA[3] study [14]. For Europe, things are far from bad, according to this study, and regarding European performance in communications, this is a reasonable claim. According to 2004 OECD Information Technology Outlook [7], six EU firms appear in the top 10 of telecommunications services firms, three in the top 10 of communications equipment and systems firms, two in the top 10 of the related area of electronics and components[4]. G. Dosi et al. comment

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[3] FISTERA is a Thematic Network on Foresight on Information Society Technologies in the European Research Area (2002-2004), coordinated by JRC-IPTS (see: http://fistera.jrc.es/).

[4] Similar results show an analysis of *triadic patent applications* in the fields of mobile and data communications. As revealed by another FISTERA study [8], European companies are among the leading players in both fields, even though not at the top. It must be emphasized, says the same

this performance as the exception in a rule that confirms an overall EU weakness to produce world industrial leaders: only 33 (13%) of the top 250 ICT in the world are based in Europe while 139 (56%) operate in US [5].

In technology sectors, firms' top positions, high shares in world exports and innovative outputs are all, somehow, conditioned from investments in Research and Development (R&D). Research in communications technologies and networks cannot be, at a financial level, "isolated" with precision within what the statistics identify as R&D total expenditures in ICT. We know however, that in all developed countries, R&D in communications (mostly in what is traditionally defined as telecommunications) is a considerable part of the ICT research envelope (especially in Europe, where ICT investments are heavily weighted towards hardware and communications infrastructures). We also know that in general, the overall level of R&D investments in ICT has felt in the last years [9] due to the financial slowdown, next to the "dot-com bubble", and to the deregulation of the telecommunications sector (telecoms operators, being privatized, have moved resources out of long-term R&D projects). But the same statistical data with respect to the European telecommunications industry itself indicate that R&D activities in telecom equipment do not show during the same period such a slow-down in R&D intensities [10].

In fact, European telecommunications sector firms maintain a rather stable percentage of revenues in research expenditures and, additionally, show good figures on communications technologies output (i.e., patents) compared with the US industry [10, 5]. Furthermore, a similar trend recently appears in consumer electronics [5], an industry that converges with telecommunications in the era of "networked appliances" (essentially due to Scandinavian countries performance). Generally speaking, in the post-liberalization era, European telecom operators and business and consumer equipment manufacturers manifest a similar, and in some cases a better R&D performance, compared to their US counterparts. And this does not apply only to the AT&T case which in 6 years, from 1995 to 2001, has reduced its R&D expenditures at a rate of 50%. Of course, AT&T's R&D decline relates to a drop in revenues and reflects the rise of the Internet in the communications business (with Cisco being the one that benefited most from it) but it is true that EU resists well in the trend of the post-liberalization era to cut R&D investments. The US has, because of the Internet, a clear innovation advantage, US IT industry produces an *excess* of applications that introduce new requirements for higher performance and ubiquitous networks, but investments in network infrastructures do not always follow behind.

The relative performance of EU telecommunications industry does not escape US policy-makers' analysis. The influential Computer Science and Telecommunications Board (CSTB) of the US National Academy of Science summarizes the situation in the US telecommunications industry as follows: *"The changes at industrial labs, the general slump in the telecommunications carrier and equipment vendor businesses, and dampened investment have all fueled concerns about the telecommunications sector. One critical issue is whether the United States is investing too little in telecommunications research today, especially in the longer-term, pre-competitive sort that is associated with sustained innovation and provides the basis for future products and services" [11].*

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study, that European companies are strong in data communications as well, a field where a number of US, like Cisco, or Asian enterprises are very actively present.

Seen from abroad, European R&D basis in telecommunications is not to be ignored: *"Although industrial research in Europe has been affected by some of the same pressures as in the United States, industrial research labs in Europe appear to be comparatively healthy and they have retained a high-quality talent pool... Major research labs associated with carriers include those of British Telecom (BTexACT), Deutsche Telecom (T-Nova) and France Telecom (France Telecom R&D). Major equipment vendor research efforts include those of Nokia, Ericsson, Phillips, Alcatel, and Siemens. U.S. companies also have a strong R&D presence in Europe, such as IBM Zurich and Motorola's lab near Paris" [ibid.].* Also, European public investments are acknowledged: *"Several major initiatives are providing government funds and fostering a more collaborative environment (industry-industry and industry-university) for telecom research aimed 5 to 10 years out. These efforts are supported by varying mix of direct government support and industry funding-sometimes derived from monopoly or quasi-monopoly circumstances… The European Union 6th framework research programs -- building on the work of the 4th Framework support for 3G wireless technology and 5th Framework support for 3G applications -- are continuing support for pre-competitive telecommunications research. In addition, most of the EU member countries have separate telecommunications research programs"*[5] *[ibid].*

Although EU is performing relatively well, an evaluation of its future position in this sector should raise some concerns. Already, whatever is the current European performance in communications, it is weaker compared to the golden days of *circuit-switched* networks. In the Internet era, communications networks escape to "telecommunications", getting more and more heterogeneous and complex, and needing to be "evolutionary" by innovating through new networking ideas that interact with the brave new world of "applications introduced from the edge" (an area in which Europe has not taken the lead) and by incorporating new expanding branches (i.e., mobile, wireless, sensor networks) in a totally seamless way. Does Europe have the right apparatus to respond to these challenges? Could this current performance in communications be declining in the future, as the Internet paradigm goes on? Additional concerns for the EU communications futures stem from its *lower,* compared with US, *research investments* and *innovative output* in the global ICT sector, as mentioned by G. Dosi et al. [5]. All those factors should be carefully considered when thinking about European position in the future, and may call for a more active communications policy which, among others, can sustain a framework to detect disruptive technological developments through the Long-Term Research (LTR) arm. Many seem to believe that for the moment this arm does not perform well. What is exactly the issue?

2.2. Research activities of EU in Communications

Communications technologies and networks is a "product line" within a vast R&D investment output where, at least at the level of global numbers, Europe lags behind the US: the total US spending (private and public) in ICT-related R&D reached, in 2002, 309 billion €, compared with 182 billion € spent in EU. In spite of these differences, EU countries' investments in ICT-related R&D are not small and should be further increased in the next years: the European Commission has

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[5] Given the high importance of the issue, the CSTB has convened an expert Committee to address the question of whether the US is investing too little in telecommunications research today, especially in the long-term R&D, which is *"associated with sustained innovation and provides the basis for future products and services"* (a project that has not been terminated yet).

targeted to boost, by 2010, R&D expenditures to 3% of EU GDP (from about 2% that is today). A part of these investments comes from EU itself, through the successive Framework Programs (FPs). The structure and the way FP-based R&D operates are well described in a parallel report on Information Technology (IT)[6].

2.2.1. Technology outlook

Within FPs research themes, communications technologies and networks compose a distinct and growing in importance ensemble. The range of research activities in this field, formally called "Network and Communications Technologies" [7], covers the following areas:

- New communications networking technologies, systems for the provision of personalized services to anyone, any time, and anywhere.
- End-to-end audio-visual networks and applications for processing and delivery of audio-visual materials, including broadcasting and in-home platforms.
- Policy and support activities in the field of Software Technologies to foster the acquisition of knowledge and stimulate innovation, and to promote global competitiveness of the European industry in software and services.
- Technologies and processes with a view to successfully tackling the security challenges posed by the 'all digital' world.
- Innovative forms of e-Business.

Two high levels visions direct the overall research work: *Ambient Intelligence* (AmI)[8] and *Next Generation Internet* (NGI)[9]. NRG vision provides the framework for network evolution while AmI

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[6] See: W. Bibel's Report on Information Technology (IT).

[7] INFSO/UnitD. See: http://www.cordis.lu/ist/directorate_d/index.html. See in particular: UnitD1 (Communications Technologies): http://www.cordis.lu/ist/ct/index.html

[8] AmI: "*Ambient Intelligence allows Information Society services to be available to anyone, anywhere, using a variety of devices. The vision is an Information Society which is much more user-friendly, more efficient, empowers users and supports human interactions. People will be surrounded by easy-to-use interfaces embedded into all kinds of objects and by an everyday environment that is capable of recognizing and responding to individuals in a seamless, unobtrusive and invisible way. Creating the Ambient Intelligence (AmI) World is the principal focus for current EU Information Society Technologies (IST) research. While it is not the panacea for all social problems, it does represent a new paradigm for how people can work and live together. y embedding IST in the very fabric of society, AmI aims to empower each individual - improving their participation in society, in social and business communities, and in managing all aspects of their lives, from entertainment to governance. Radical social transformations are likely to result*". (http://europa.eu.int/information_society/policy/ambienti/index_en.htm).

[9] NGI: "*The Web and email are just two applications which can be run across the Internet. More are on the way, and European mastery of them will be essential if Europe is to reap the benefits of the Information Society. Tomorrow's internet will play a crucial role in developing the EU's vision*

wants to be a human-centered and industry-widely accepted vision for technology development focusing on future technological generations in which appliances, interfaces, applications, networks will be more integrated into the everyday environment, through seamless interactions. The ultimate objective is to develop and render accessible to all a multitude of multimedia, high bandwidth and anywhere-anytime available services [12].

This apparatus features also two particular structures oriented towards more long-term and "high-risk" research (covering of course broader issues that the communications technologies and networks field itself): the FET Programme[10] (notice in particular the recent initiative on "Situated and Autonomic Communications"[11]) and the NEST Programme[12].

2.2.2. EU policy responses

From a policy perspective, these technology initiatives subscribe to a set of ICT policy goals which are defined by P. Johnston (EC), in his very dense presentation at EuroCPR 2004 Conference, as follows [13]:

- i) Industrial policy to consolidate the European ICT sector for a single market and as a globally-competitive private sector, rather than as public monopolies or 'national champions'.
- ii) Consumer welfare policies to provide a wider range of more affordable communications services to all Europeans.
- iii) Policies for sustained economic growth stimulating innovation across all the economy, including in the provision of public services.

How successful have these policies been, and how effective is the R&D that comes out from these contexts, these are interesting issues but they are not exactly in the scope of this report. In these

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of Ambient Intelligence – where Information Society services are available via intuitive interfaces to anyone, anywhere. Tomorrow's internet will therefore be: i) Faster (Broadband) and more Secure, two eEurope 2005 policy priorities; ii) available everywhere, on more platforms: Making Information Society services more accessible to more people means liberating them from the 'tyranny of the PC'. In a "multiplatform" approach, both mobile internet devices and digital television could play key roles; iii) smarter: While today's internet is good at carrying data, it does not have any inherent intelligence - it does not understand the data it carries. The Semantic Web will change all that; iv) more powerful: the IST research programme is also helping Europe build Grids, which are going to revolutionize computing as profoundly as email and the Web revolutionized communications and publishing; v) empowered by IPv6. IPv6 is a key technology for the Next Generation Internet. Rolling it out as quickly and as widely as possible is essential to achieve the above objectives".
(http://europa.eu.int/information_society/policy/nextweb/index_en.htm)

[10] http://www.cordis.lu/ist/fet

[11] http://www.cordis.lu/ist/fet/comms.htm

[12] http://www.cordis.lu/fp6/nest.htm

days there is an ambient pessimism about EU global performance. Yet, it is not unreasonable to accept that because of the commonly funded R&D, Europe has been endowed with a set of ICT policy institutional mechanisms and has sustained a collaborative research environment among business and between business and academic institutions. With respect to the communications matters, P. Johnston is right to observe that EU policies have been successful to enable a more consolidated industry structure and *"consolidation and competition have achieved economies of scale and scope, with subsequent price reduction for consumers, and a wider range of services available to more people" [ibid.]*. However, several questions remain about the capacities of this apparatus to "trigger" innovation and many of them are now raised by the communications research policy community. Since the last EuroCPR Conference, a fertile discussion in this regard has been publicly established (see following Box).

Box 1: A EuroCPR policy debate[13]

Contradiction, Confusion and Hubris: A Critical Review of European Information Society Policy, by N. Garnham: "…The problems with information society policy and related research are firstly that they are based on a faulty analysis of the underlying difficulties facing the EU in terms of competition with the US. Second, even if we accept the underlying analysis and the Lisbon goal there is no evidence that we in fact have the policy instruments that might produce the desired result. Thirdly, this is in part because the theories and models underlying policy formulation and implementation are much more controversial, partial, doubtful and contradictory than either theorists or policy makers are prepared to admit. And this is in large part, as Bauer has stressed, because what the world theorists are trying to understand and policy makers to steer is inherently more complex than either researchers or policy makers feel comfortable in admitting to. This then leads me to my final conclusion that we must take all grand visions, plans and theories with a very large pinch of salt. This is not, I must stress, an argument against public intervention and in favour of letting the market rip, although versions of it have been used as such. Market messianism is subject to the same critique. We know that markets are of different types, are messy mixtures of private actions and public rules and institutions and have extremely unpredictable results. Now the message is that both researchers and policy makers need to be much more humble. We cannot, I think, avoid policies and regulatory interventions. No human society or social group can be unplanned in that extreme sense. The best we can hope for is messy, short term interventions in specific areas to solve specific problems. There are no general answers or rules and the results of intervention are likely to be very different from what was planned".

Strategic Interests in Information Societies, by R. Mansell (LSE): "…In his speech Nicholas Garnham acknowledges that 'policy was driven by a range of different interests with differing definitions of the problem, different aims and different supporting economic models and theories', and yet he also asserts that policy makers 'want to please everyone'. As an academic with an enormous command of the history of European economy and the economic determinants of innovation and competitiveness, it comes as no surprise that Nicholas Garnham should want the research community to unravel specific interests, problems and goals, and their alignment with different economic models and theories. Is it any wonder that there are contradictions between

[13] Full documents available at ERCIM web site: http://www.encip.org/garnham.php

industrial policy initiatives and the drive to liberalize markets and stimulate competition in the ICT sector, given the array of economic interests that are at play in Europe? Clearly, different business interests stand to gain from different approaches to information society policy. However, when it comes to the collective processes of governance within which policy makers operate, Nicholas Garnham seems to lose sight – at least in this speech – of the highly differentiated interests of policy makers themselves – interests which, while certainly contradictory, do not extend to pleasing 'everyone' when 'everyone' is taken to include citizens as well as firms and regulatory institutions. Contradictions between the interests of those who advocate industrial policy and those who support the strengthening of competition in the marketplace are no surprise, but neither is the tendency for policy makers to lose sight of the citizen's interest in favor of other interests...".

Half-Empty and Half-Full Glasses, by W. Steinmueller (Univ. of Sussex / SPRU): "…The knowledge-based economy and the information society are inextricably linked concepts in which the tools provided by advanced communication and computing technologies are of central importance in meeting human aspirations. The problem is that, as in all human endeavor, the aspirations of the participants are in conflict. Unlike traditional goals of public administration and management, the politics of the information society are under-developed and unbalanced. The supply side voices have for too long dominated the discussion, to the extent of suppressing other voices and even pushing them into a sort of 'underground' whose most visible manifestation is the free/libre open source software movement in Europe and other countries. As Eli Noam noted some years ago, networks have politics. Many of the inadequacies of our current policy frameworks are the consequence of failure to make a break from the politics of the past. Championing large industrial players prolonged and heightened the processes of re-adjustment and re-structuring. Embracing the new 'insurgent' Schumpeterian competitors is likely to be just as damaging. Restoring the 'user' and the concept of 'public welfare' to centre stage will go a long way towards addressing the policy disconnects that Nicholas Garnham correctly identifies".

Are Industrial Policies Irrelevant or Obsolete?, by A. Henten (Technical Univ. of Denmark / Center for Tele-Information): "…A reading of Nicholas Garnham's address leaves the impression that he sees the major problem lying, at present, in industrial policies – the Colbertism of European Union policies as he denotes them. He stresses more than once in his address that there are also problems involved in the market models and competition promoted in recent years, and in reliance on letting the market rule. However, the main focus of his concern is on the side of industrial policy. And, this may be justified in the sense that industrial policy has received the most emphasis in recent EU policies. After the big move toward liberalisation of the telecommunications area and the introduction of competition, there is now much emphasis in EU policies on the development of broadband access, and services requiring broadband capacity (the Lisbon strategy). Nicholas Garnham is worried that such industrial policies may be unnecessary, and probably even wrong and a waste of public money, if economic support of various kinds is involved. The reason, according to him, is that we understand the complex reality in a much too simplified manner. An alternative point of view might be that state intervention in different kinds of industrial policy moves is necessary to support markets and make them function in the best possible way. According to this view, state intervention cannot be limited to mere regulatory measures, but must also encompass industrial policy initiatives on the supply as well as the demand side. The dangers in such a point of view are obvious. Formerly much industrial policy was criticized for supporting dying industries on the basis of pressure from often unclear alliances between the owners and the people employed in them. Such industrial policies still exist, but are being superseded by policies supporting new industry areas such as biotechnology, nanotechnology and ICTs. But even here, there is a great risk in ‘picking the winners’, as the winners chosen may eventually be out-competed by similar winners in other countries reproducing the same industrial priorities. And, even in a situation where the choice was ‘right’ in the sense that a successful industrial development is achieved, one might question the necessity of supporting industrial development with public money that could have gone into, for instance, social programmes. However, in spite of these reasonable objections there may still be a need for industry policies which – on either the demand side or the supply side – support upcoming industries. Analyses of industrial development successes around the world often identify government intervention in the shape of industrial policy initiatives as one of the important building blocks…”.

There is much merit in this discussion about the performance of EU Information Society policies but this report is on research in communications technologies and networks only. While the research policy community debates at a macro-level and wants to establish processes to “learn from failures”, to improve EU policies, other researchers claim a different “failure”: the increasing importance, during these last years, attributed to the “demonstrable usefulness” of research that finally works to the detriment of both basic research and innovation capacity. The issue has been recently raised by various expert reports and discussed in workshops and conferences, among them the report of G. Dosi et al. [5] on the European weaknesses in innovation as a result of badly considered research options. Already, a few years ago, K. Pavitt has sounded the alarm by explaining that US practice in basic research, considered as example to mimic, *“has often been misinterpreted as being driven by short-term usefulness, whereas it key features are massive and pluralistic government funding, high academic quality, and the ability to invest in the long-term development of new (often interdisciplinary) fields” [14].*

This strange situation is now acknowledged by the EC which recognizes in the project to create a European Research Area (ERA), a certain deficiency in explicitly taking into consideration the issue of basic research[14]. But possibly the consequences of “having downsized” basic research are not yet well understood. The high priority given by EU research policy to “user-defined” technologies and services, and “applicable” technologies, may have produced more from the “improving on the existing” than from the “designing the disrupting”. Obviously, these policies towards research that embeds IST in application have been thought in the context of an effort to move away from “older” very technology-push service offerings, but they now have certainly attained their limits. FISTERA[15] project seems to detect the problem. The project summary document makes explicitly the link between the need for “pure research” and the aptitude to *“be able to detect potentially disruptive technologies” [6].*

Basic or “pure” research is supposed to be situated in a long-term perspective in the sense that the technological solutions to which this work gives rise are unforeseen in a very “applications context” and, if they come out, move far the technological frontier and of course create new value opportunities. To understand the importance of the long-term research in technology breakthrough sectors, we can look for instance at what happens now in the wireless networks area. EU invests the most of its research effort on the “mono-culture” of 3G/4G technologies (the “linear” extension of

[14] See: EC, Communication from the Commission, Europe and Basic Research, COM(2004) 9 final.
[15] See: footnote 3.

GSM technology wave), in a very Lisbon-based perspective of broadband ubiquitous access heterogeneous networks allowing the seamless delivery of wireless multimedia services. This perspective seems to understand Wi-Fi technologies, i.e., the technologies offering to homes, businesses, university campuses etc. the possibility to create local area networks, as a simply different access architecture over which applications and services should seamlessly provided. This is not wrong and it will certainly happen. But maybe Europe is going to fail to understand what the contribution of the "commons-based peer production"[16] may be to the organization of the wireless networks…

In the US, researchers, now funded by DARPA[17], experiment with very "beyond-the-frontier" solutions that could apply years later, and revisit much of the state-of-the-art "problem solving" (by trading off bandwidth and power to challenge our receptions about "interference" – that property of radio waves which has justified in the past the method of allocation of spectrum on the basis of functionally separated frequency blocks and we have longtime considered as a principle impossible to defeat). Obviously, we are here in a long-term research perspective which envisages exploring *commons-based behaviors,* in a world of *unlicensed spectrum,* and designs agile and collaborative architectures for networks that, in flagrant contrast with how conventional systems work, increase their capacity as the geographic density of users increases. In Europe, much of the technology development that is prerequisite for such an evolution seems to exist (the so-called "software radio" technologies[18] and "Ultra Wideband (UWB) transmission systems" whereas IST has even to show a "cluster" of activities[19]). But EU contribution in the "wireless commons" debate is limited to only regulatory views. Wireless experiments with novel architectural views are very dispersed and will certainly lack any interdisciplinary input. Maybe because there is no a long-term research agency to craft a framework for research on open wireless architectures[20]…

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[16] Defined initially by L. Lessig [15] as the *"part of our world that we all get to enjoy without the permission of any"* which constitutes the *"core of the open society",* the "commons" have been rapidly established as a novel concept in the literature of organizational sciences. In the light of the growing contributions in the subject, the term seems now to define a social networks-based peer production model where *sharing among weakly connected participants* (i.e. pooling large numbers of small scale contributions to achieve effective functionality) create, in some cases, the basis of an efficient system of allocation of resources [16]. Open source software, song sharing, distributed computing, the volunteer-written online encyclopedia Wikipedia, and other forms of effective social production offer clear examples of large-scale sharing of resources, imposing as an efficient organizational practice.

[17] See *infra.*

[18] See: Workshop on "Cognitive Networks and Radios", organized by Dagstuhl (http://www.dagstuhl.de/About/index.en.html).

[19] See: http://www.cordis.lu/ist/ka4/mobile/proclu/c/uwb/uwb.htm

[20] It is worthwhile to notice, to contrast with what we report on wireless technologies outcomes, the success of European research in another important area for *collaborative networking* research, those of Grid architectures. A comparative study of the two cases study would be very fruitful to learn more about how Europe should develop capabilities to harness the architectural complexity of the today networks.

2.3. The need for EU to set long-term but effective research priorities in communications

Essentially, the need for basic research comes from the complex nature of the modern communications networks and the re-organization of the industry itself next to the introduction of liberalization and competition. What is particular in modern communications networks, as in many other complex systems, is the extreme heterogeneity of the parts and their patterns of organization that involve various hierarchies and multiple scales and yield high performance and robustness because of this complexity in organization.

The key to manage complex systems requires copying with such an extreme diversity, notices with intelligence a recent report issued from within the FET Community which wants to promote the application of Complex Systems approaches in problems of system complexity that the industry faces today [17]. Part of this "diversity management" is embedded in *architectures*[21] that implement very specific internal structures usually involving some coordination achieved through arrangements for the interconnection of internal parts[22] – also described as "coordination by design" in the sense of a coordination system with rules "embedded" in the technology itself. But beyond design, coordination is also a collaborative solution that emerges from the interaction of the organizations that operate and use these networks. These organizations, to refer to an experienced thinker of the complexity in information systems[23], respond to a multitude of diverse economic interests, *"in varying relationships of collaboration and competition with each other"*. This suggests that the tools and the insights for understanding and managing this emergent coordination should come from theoretical investigation. There are several theories which in these last years have addressed the problem of network formation, evolution and coordination, labeled as network research theories or, simply, *network theories* (a term that encompasses various approaches from Game Theory to statistical physics).

For practical reasons, network architectures and network theories and models, as well as the interdisciplinary approach they frequently demand, and many other aspects of the networks of tomorrow, are not in the immediate horizon of research performed within the communications industries, or in the context of "pre-competitive" collaborative research. In the past, a lot of research of this sort, producing new fundamental knowledge, was performed within the research labs of the telecom operators. As the operators underwent privatization in the late 1990s, these labs have been "downsized" and the level of research has dropped in general. Besides, attention has shifted somewhat from core network technologies into research on application enabling technologies and

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[21] As pointed out by C. Baldwin and K. Clark [16], large complex systems require design architectures. A design architecture divides a system into parts and set-up interfaces between these parts to allow for efficient conversation between them and modular construction and development. Similarly, architectures in communications networks provide a "reference model", a set of abstract organizing principles and structuring relationships among the network's components that guide the technical design of the network, especially the engineering of its protocols and algorithms [17]. Architectures are increasingly considered as highly valuable frameworks through which *"knowledge comes to be organized to create wealth and welfare in a modern economy" [18]* and hence they acquire an importance in the research of the knowledge economies.

[22] For a cogent description of how "complexity matters" in large scale technical systems, see the work of J. Carlson and J. Doyle – see reference [20] and *infra*.

[23] C. Papadimitriou from Berkeley University; see reference [21].

customizable network solutions [11]. The liberalization has in effect accelerated a tendency towards more genuine long-term research to be located within equipment manufacturers premises (Ericsson, Lucent, Nortel and Nokia are the most dynamic in research activities), with telecom operators being more involved in shorter-term technology development [10]. Both however are essentially interested in new services design and service infrastructure development, which should certainly be undertaken in close interaction with users. They also put particular emphasis, prompted by financial imperatives, to migration paths to new infrastructures that enable these innovative services offerings to be delivered. How then to get involved in research with uncertain financial ends when innovation with respect to service development, and to business models supporting these services, requires systematic focus and financial discipline? It is the same for the EU "pre-competitive" research. It can not avoid to follow somehow these trends towards new service infrastructures, if the objective is to stimulate, through research, not only the innovation across all the economy but also the competitiveness of the European equipment providers (and of their complex supply chains) which should efficiently operate as multinationals firms within increasingly globalized markets.

This might imply a need for a new research pole, relatively independent from short-term business strategies, which might cultivate *high impact/high risk* long-term visions[24] and carry out "open research" activities that complete those undertaken in the context of pre-competitive collaborative research. In US, there is DARPA, the Defense Advanced Research Projects Agency (and NSF, the National Science Foundation to some extent), to organize research along these directions, very often not directly linked to military or industrial needs[25]. Research of this nature can contribute to resolving key "public interest" networking problems, stemming from the multi-level complexity of the Internet, and to elucidating the complex structure and organization of the emerging digital world. It is supposed to provide a *"body of understanding"* and at the same time, as R. Nelson nicely explains, applies to *"solving particular kinds of practical problems, and advancing bodies of practical technology" [23]*. Very likely, such a long-term research in communications that leads to a "body of understanding", reflecting itself on the "body of practice", should of course *"push back the trend towards increasing appropriablity"*[26], but it should also be effective[27] in the sense of:

i) Recognizing and selecting key-research areas "full of open problems", with high impact in the evolution of the communications technologies and networks.

ii) Using a mix of different perspectives, ranging from basic to high-level applied research and systems engineering – and call for strong interdisciplinary support.

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[24] To use the proper terms of FISTERA project' summary document which also asks for re-examining the balance between *market-driven/low risk* and *high impact/high risk* research [6].

[25] However, several critical voices in the US complain about the inadequate level of support for basic research in communications technologies and networks. In this regard, see in particular the presentations in the "Workshop on Basic Research in Telecommunication" held on May 2003, hosted by Columbia University (Columbia Institute from Tele-Information) [22].

[26] In line with the report of G. Dosi et al. [5].

[27] G. Dosi et al. [5] may be sarcastic with some "pre-competitive" research fellows that *"try to tap community money in areas that are marginal enough to not justify the investment of their own funds"* but one should not ignore that long-term research "ideals" have frequently justified, in many European countries, long-term researchers' carriers within bureaucratic and conservative research institutions funded by national money.

iii) Addressing the relevant policy issues which are necessary to stimulate technology transfer from research to application.

To sum up, support for long-term but effective research priorities should be justified in terms of providing a broader horizon, necessary to the "disruptive" innovation, and facilitating downstream exploration – long-term research is to be used to produce further research or application. From this perspective, it might be classified as public infrastructure that is "consumed" as "abstract" input into a wide range of research and application activities, thus yielding large positive externalities [23]. Hence, a *commons-based access* approach to long-term research results should be considered in the sense of pro-actively organizing a "public space" where business action and regulatory decisions can "openly" borrow "cognitive resources" to produce more efficient and desirable outcomes as technology changes and commerce grows[28]. Ultimately, this kind of research should be regarded as framing the long evolutionary technology cycles, i.e. techno-economic paradigms [24], and especially the transition of shorter phases (of 20-30 years duration each) during every long cycle which are: a first installation stage (where Schumpeterian "creative destruction" happens somehow) and a second deployment stage (during which the new paradigm establishes and delivers its full potential for growth) – separated by a short period of uncertainty (the so-called "turning point").

In the following sub-section, we turn again to the "concrete", i.e., the complexity of modern communications networks, to explain how the ability of seizing future opportunities stemming from "new departures" within the current evolutionary cycle[29], is conditioned by the level of understanding of the multiple transformations of the Internet. That understanding which long-term research often probes for. At the same time, by reviewing the evolution of the Internet, we delimit

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[28] A new research project at Columbia University defines now "commons" as the set of rules, standards and governance within which all exchanges (including markets) take place – which might be the framework to consider "long-term yet effective research". For further details, see the Workshop on "The Economics of the Commons: Organizing Private Transactions in Communications", Columbia Institute for Tele-Information, May 2005, (http://www.citi.columbia.edu/).
Note: We acknowledge interesting discussions with A. de Fontenay (Columbia Institute from Tele-Information) on this broader notion of "commons".

[29] As Internet evolves towards the deployment period, it is normal to expect "architectural" or "modular" innovations – those innovations having the higher "breakthrough" potential within the limits defined by an ongoing techno-economic paradigm.
Note: The term "architectural innovation" refers to innovations that change a product's (or system's) architecture but leaves the components, and the core design concepts that they embody, unchanged; while "modular innovation" (applying at the level of the components of a product or a system) involves replacing one or more core design concepts without changing the system's architecture (or, eventually, extending this architecture with new components based on novel core concepts). Both, appear once a technological trajectory has been established and contrast with "incremental innovations". This term describes only "normal" technical changes appearing as simple improvements of existing components and product's characteristics. For further detail, see references [25] and [26].

the area under investigation and start recognizing key areas that lie at the core of the evolution of communications technologies and networks.

2.4. The "cognitive" rationale for long-term research: understanding the Internet evolution to realize future challenges

2.4.1. A little bit of (pre-)history

Research in communications technologies comes from the very old days of the Telecommunications industry. For many years, telecom operators in US, Europe and Japan, have been massively investing in long research they needed to evolve their networks – with Bell System and AT&T being the seminal case of a protected, regulated and highly innovative monopoly. For many years, telecom operators were funding "in house" research, performed within Research Labs tailored to (network and equipment) R&D purposes – such as AT&T's Bell Labs, France Telecom's CNET, BT's Research Laboratories. NTT's Electrical Engineering Laboratories etc. – frequently collaborating with selected academic institutions with which they entertained long-term relationships. It is the "golden era" for communications research (from 1930s to 1970s and 1980s). In these times, researchers within Telecom Research Labs were enjoying remarkable "problem solving" flexibility and the resources to address a variety of issues, from complex theoretical networking problems to new network architectures and successive generations of network equipment and so forth. The list is long and includes even early "interdisciplinary" issues as the study of the social patterns underpinning the adoption of the telephone service and the design of effective and socially optimal pricing policies. Many of the pioneering innovations that shaped the face of the world (from the transistors to microwaves and laser) and abundant new knowledge (including much from the mathematical theory of information and the Industrial Organization economics) has resulted from basic research conducted only at Bell Labs [27, 28].

In the post-liberalization era, very little from these R&D structures tailored to a monopolistic industry organization, remained in place [10, 11, 27, 28, 29]. Progressively, starting from the 1970s, research in the field of communications technologies became "fragmented" and "commercial". First, telecom operators have dropped out from research, design and development of telecom equipment, leaving this activity to specialized equipment and technology suppliers, as Lucent, Nortel, Nokia, Ericsson, NEC, Cisco etc. Today, telecom equipment companies grow and compete on the grounds of the innovation and product differentiation, and considerably invest in R&D activities (R&D investments go up to 10-20% of their revenues from sales). But these investments, as explained earlier, apply to new services design and to novel connecting-to-the-network-devices or target to improving the efficiency of core network equipment (routers, switches etc). On the other side, telecom operators have downsized the level and the resources committed to primary long-term R&D, as a result of the radical change in the industry structure (from monopolies to increasing competition in the global markets), to concentrate on business development and competitive success through commercial R&D (i.e. short-term, applied, research on application enabling technologies). In a few years, the famous R&D Labs of the telecom operators have simply disappeared or shifted their creativity to craft customized network solutions and product-related R&D. Fundamental networking research, almost an "ideal" for telecom engineers, is not exactly part of their main preoccupations[30].

2.4.2. The impact of the Internet and its evolution: understanding the "texture" of the ongoing technological change

The dis-integration of the old "vertically integrated" network into a "layered" communications architecture (network service, network infrastructure, equipment) where very different companies compete to gain customers and impose global presence [29], was not, however, the essential force that altered the structure and the evolution of the industry. The big change in the profound nature of the electronic communications, and in the way in which researchers, engineers and technologists think about problems and solutions, comes with the data communications networks and the Internet.

2.4.2.1. The initial condition: The IP separator

The computer industry technologies enabled first the development of separate private networks for data transmission, at the margin of voice-centric telecom operators' infrastructures. Then, they made possible the progressive interconnection of these networks to a "network of networks" – through the massive adoption of the Internet networking protocols (TCP/IP) across the communications landscape. In a very short time, the Internet standards became the basis on which new communications applications are being crafted. The Internet altered profoundly the organization of the communication infrastructures in the sense that it has enabled the separation of applications and service offerings from the "underlying" infrastructure facilities" [30, 31, 32]. This happened by defining, as Figure 1 shows, an interface (Internet Protocol, IP) to the basic technology substrates and then exporting that interface for application development.

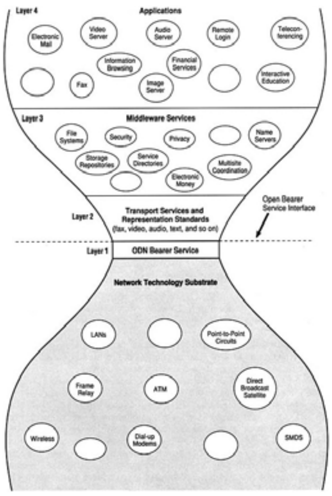

Figure 1:The Open Data Network model

[30] What is fundamental basic research in communications is traditionally understood in terms of theoretical innovations in information science and telecommunications (transmission, switching, network operation and management etc.) which are expected to evolve into practical results in a period of 10-20 years. Today, of course, such a list of networking themes for basic research should be more broadly defined (see *infra).*

From this interface any number of diverse applications may be constructed, with no obligation to modify anything in the technologies prevailing at the (underlying) layers of network substrates. The World Wide Web (WWW) is the first and notorious example of such a new generation of non-anticipated applications. Hence, applications are not pre-specified in the network architecture design but emerge during the network's evolution process, they are "edge-based" (i.e., applications being independent from the network means that their functionality is hosted in computers attached to the "edge" of the network). And applications are thriving. Streaming video, IP Telephony, applications for mobility and collaboration, online gaming, instant messaging / presence are some of the more characteristic examples of applications that have been developed independently of any underlying network technology and cross over multiple network infrastructures (including mobile networks).

The dynamics of proliferation of new applications over the Internet need to be clearly understood since this proliferation appears to be the most critical factor of Internet success. In the telecom networks, applications (not much in fact, essentially telephony and fixed data services over circuit-switched packet networks), were tightly coupled to a specific infrastructure: a dedicated infrastructure, for example PSTN or telecom data networks, was used to realize separate applications, voice and data transmission correspondingly. In this context, innovation patterns at the network technologies dictated the path of technical change at the applications and services level (i.e., network technologies defined the set of applications). With the Internet, the communications industry moves to a "horizontal integration model" (see following Box), where diverse applications are developed independent of any underlying architecture, thus obtaining an acceleration of the innovation path in the communications industry [33]. In this model, the IP protocol acts as a short of logical translator: it enables a "spanning layer" located on top of the transportation modes that pairs applications (and services) to infrastructure facilities. Applications request network service from the spanning layer, not the underlying infrastructure, and the spanning layer translates a request for network service to the network infrastructure protocols. From separating the communications infrastructure in two blocks, infrastructure facilities at-the-bottom, applications and services on-the-top (with the IP spanning layer realizing the minimal functionality that is necessary to make these two blocks interoperating), openness to innovation (to new applications and new uses) became a de facto condition[31]. We have associated the Internet design with the "open flexible specialization model", a more generic trend on the evolution of industrial production modes, that includes those systems where the set of variable design features and the domain over which each variable feature ranges are both potentially infinite [31][32]. This explains why the Internet continuously evolves and successfully integrates new functionality through an ongoing coordination process.

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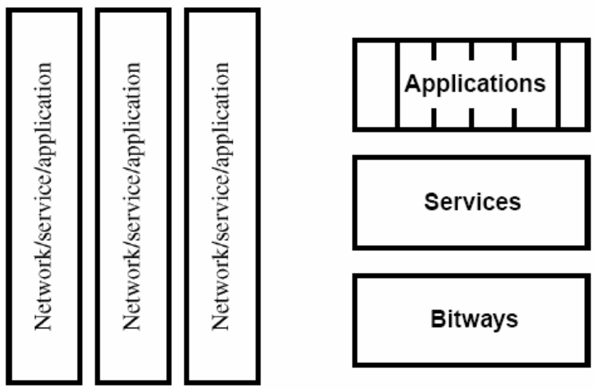
[31] The two-blocks Internet structure became a valuable resource for application innovators to come from anywhere to draw upon (note: what also happens in the Internet is that *transparent packet carriage* allows for deploying new network protocols without having the obligation to modify the "inside" of the network). Because of this openness to innovation – to new applications and new uses – L. Lessig calls the Internet an "innovation commons" [34].

[32] Drawing upon M. Piore [35] description of the transformation of industrial production systems towards greater variety and flexibility as a four-stage evolution: *mass production, flexible mass production, closed flexible specialization* and, ultimately, *open flexible specialization.*

Box 2: The horizontal integration model

D. Messerchmitt [33]: “There are two architectural models for provisioning networked applications. In the most extreme form of vertical integration, a dedicated infrastructure is used to realize each application. The premier example is the public telephone network, which was originally designed and deployed specifically for voice telephony. In contrast, the horizontal integration model is characterized by:

- One or more integrated bitways that transport integrated data and stream media like audio and video with configurable quality-of-service (QoS) parameters.
- A set of services, such as middleware services (directory, electronic funds transfer, privacy key management, etc.) and media services (audio, video, etc.) that are made available to all applications.
- A diverse set of applications made available to the user.



A key advantage of the horizontal model is that it allows the integration of different media within each application, as well as different applications within the bitway. (For this reason, this is often called an *integrated-services network* in the telecommunications industry).

But before looking closer to the Internet evolution, a conclusion is evident: equipment design and development first, and then applications’ development, have been dissociated from the lower, in the protocol hierarchy, network substrates (physical and logical data transmission), to prevail as independent modules of an increasingly complex communications edifice (many talk about *info-communications* prevailing now over tele-communications) [27, 36].

2.4.2.2. “Normal” evolution on the trajectory

Two other major evolutions complete the picture of the transformation of the communications field during the last years: the rise of the mobile networks as a de facto infrastructure for voice traffic and several shifts in Internet’s structure and governance.

1. At the turn of the millennium, households and businesses opted massively for the mobile telephony, which started then to progressively replace old fixed telephony. Today, in all developed countries, including slow-moving-in-the-cycle United States, evolving usage

patterns suggest that mobile and fixed telephony will become ever greater substitutes over time [37]. And, industry observers expect that, by 2009, 50% of all voice calls will be made by mobile phones[33]. In few years from now, mobile telephony and VoIP (which stands from voice-over-the-Internet) will impose as standards modes for voice traffic and cannibalize the total of legacy voice revenues. This will also create unprecedented tensions for seamless integration between the Internet and the mobile networks and require to crafting new, appropriate to the situation, economic and regulatory approaches.

2. The Internet has born and grew up as a public network environment, *coordinated by design,* as S. Gillett and M. Kapor have described [38] a few years go. From an organizational point of view, it looks like a *confederation* of independently managed networks (and computers) with a high density area in the "middle". In the Internet, end-users' computers, or edge networks, connect directly or indirectly (through local aggregators' infrastructures) to the "cloud", which is the statistically shared wide-area transport backbone making the "core" of the Internet. To use a metaphor from transportation, any computer or edge network access provider simply provides transport to a "hub", or exchange point", from where end-users' IP packets can hop to another link and finally (maybe after several hops), reach their destination. These exchange points are powerful computers and are provided "in quantity" from the backbone providers to their customers (local aggregators and edge networks). Ultimately, the excess of bandwidth in the "core" and the existence of many exchange points for interconnection work together, and efficiently play down the probability of "bottlenecks" in the transport of data from one part of the Internet to another.

   Looking more carefully at the Internet map, one can easily understand that the bandwidth which is abundant in the "core", at least currently[34], is missing at the edge. Naturally, as the Internet prospers and evolves, there is a real need to extend high-speed connectivity from the exchange points to users premises in homes, small businesses and smaller offices of larger organizations, local governments etc. This is known as the "last-mile broadband" problem[35] of the modern communications infrastructure and it is a real difficult problem with many technology and economic equations to resolve (with the question of *industry governance* resurging in the public debate). It also explains the fact that the Internet architecture extends by acquiring new branches, like the WLANs and the ad hoc networks, emerging now as alternative options to provide broadband connectivity (together with sophisticated mobility) – thus adding more diversity to an already complex communications infrastructure[36].

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[33] See in particular http://www.soundpartners.ltd.uk/article_fixed_mob_sub.htm

[34] Although the requirements for ever higher bandwidth connections never stop.

[35] Strictly speaking, the "broadband challenge" is not defined only in terms of a high bandwidth link but on the basis of a whole set of performance characteristics (speed, latency and jitter, symmetry between upstream and downstream capacity, always-on and so forth) for Internet service at the "edge".

[36] Wireless and ad hoc network, as well as sensor networks (another powerful new ramification of the Internet), have very different goals from the current Internet for applications design and propose some novel ways of routing information.

Such network ramifications at the edge, work together with new generations of applications towards a structural metamorphosis of the core. D. Clark and M. Blumenthal [39], echoing concerns of the US research and communications policy community, describe in a recent and very influential paper this metamorphosis as a serious "threat" to what the Internet community understands as the more valuable asset of the Internet design, the "end-to-end arguments" (see following Box). What are the sources of metamorphosis? They define several points: i) The Internet evolves to a "multi-party network" as a result of the expanding streaming audio and video, peer-to-peer and Grid applications and other complex gaming and mission-critical networked enterprise applications requiring "almost instantaneous" and "role-based" service; ii) There is an acceleration of the deployment of applications based on intermediate servers (like storage sites that brings "far a way" content close to the customer who requires access to this content or, to give another example, instant messaging servers) [37] that introduces practices of two-stage application delivery; iii) Computer attacks and end-nodes that want to "force" interaction with other end-notes (as is the case with spam e-mail or Trojan horses-like software) have become a very common situation in the Internet, with, as a result, the multiplication of firewalls and "application filtering" software – establishing "local" impediments in the end-to-end application connectivity [ibid.].

Box 3: The e2e argument

The end-to-end arguments (e2e) are twenty-five years old. In 1981, in a paper named "End-to-End arguments in System Design" [40], J. Saltzer, D. Reed and D. Clark propose a *theory* for distributed computer systems design, that builds on the ARPANET experience, recapitulated in a basic argument: "*functions placed at low levels of a system may be redundant or of little value when compared with the cost of providing them at that low level*". The end-to-end arguments have marked the design of the Internet since they served as the rationale to move applications' functionality "up" (in the layered networked hierarchy) and "out" (to the "edges" – and not "in the core" of the network). As explained by Clark and Bluementhal [39], "*The end to end arguments concern how application requirements should be met in a system. When a general purpose system (for example, a network or an operating system) is built, and specific applications are then built using this system (for example, e-mail or the World Wide Web over the Internet), there is a question of how these specific applications and their required supporting services should be designed. The end to end arguments suggest that specific application-level functions usually cannot, and preferably should not, be built into the lower levels of the system – the core of the network. The reason why was stated as follows in the original paper: The function in question can completely and correctly be implemented only with the knowledge and help of the application standing at the endpoints of the communications system. Therefore, providing that questioned function as a feature of the communications systems it self is not possible*".

Not only structure but also governance of the *confederation* is undergoing change. In the Internet, interactions among *members of the confederation* are administered, as suggested earlier, by an explicit set of minimal common rules that are embedded in the IP protocol: a

[37] The so-called *middleboxes* which contain *application-layer servers.*

delivery service (datagrams or packets) and an identification scheme (IP addresses). This is IP connectivity. But, although it looks like the *common currency* of the Internet exchange system (and it is), IP connectivity has complex industrial economics that distance it from a commodity product in a wholesale market. IP connectivity has evolved, as expected [31], to a product with relatively low demand elasticity of substitution in a market where, in fact, various Internet Service Providers (ISPs) compete by differentiating each other on the grounds of the *network service* they can offer to applications requests coming from their customers (i.e. other ISPs or edge networks). Network service means enhanced data transport service and this is what explains ISPs' strategies aiming at: i) over-provisioning their backbones in bandwidth, ii) deploying, within their networks, intermediate storage sites, and *middleboxes,* that position content close to the user who requests access to this content [39]. But the rise of ISPs in the Internet adds a clear condition in the way innovation is introduced in the Internet: innovations aiming at improving the *network service* of the Internet come now from the ISPs or, it is very difficult to see innovations designed within research laboratories, or elsewhere, to be adopted without the consent of the powerful *ISP group* (RSVP, and more generally explicit *Quality-of-Service* deployment over the Internet, are victims of ISPs' reluctance to move beyond current QoS standrads[38]).

Box 4: The Internet Architecture in Reality

Internet Architecture in Reality: An Assembly of Inter-dependent Protocols

[E. Gelenbe, Imperial College]

- ✓ The Web is one possible "Standard User Interface"
- ✓ TCP, the Transmission Control Protocol: Controls Packet Flow for a Connection as a Function of Correctly Received or Lost Packets (TCP Reno, Vegas, etc.) & Retransmits Lost Packets
- ✓ BGP: Determines Paths between Clouds of Routers belonging to Autonomous Systems (AS)
- ✓ MPLS: Carries out fast Packet Switching based on Predetermined Paths within AS using Labels, and Implements Traffic Engineering within AS
- ✓ IP (Internet Protocol) Implements Shortest Path Routing within AS. Variants of IP Address QoS (e.g. IPV6), Weighted Fair Queueing, Congestion Control through Packet Drop…

[38] RSVP (RFC 2205) stands for Reservation Protocol and wants to enhance the current Internet architecture with support for Quality of Service flows. The RSVP protocol can be used by a host to request specific qualities of service from the network for particular application data streams or flows. RSVP can be also used by routers to deliver quality-of-service. In spite of its advantages, RSVP protocol has never been adopted by the ISPs, thus remaining a technology with potential but no-application.

2.4.2.3. Techno-policy turmoil and the imperative need for novel architectural considerations

Naturally, as the Internet rapidly changes, people debate over the actions to take in order to face change. Today, the "end-to-end argument" is at the center of a *Broadband Debate,* involving several disciplines, from computer science and networking to economics, law and sociology, and many ambitious academics, policy makers and industry lobbies' leaders. Strangely, this debate had not found a real echo in Europe. Abroad, it creates public passions and serious divergences about future Internet policies. The main issue is about how to regulate the upcoming migration to broadband but essentially it is the original architecture of the Internet that is now *under siege.* The debate is somehow polarized between *openists* and *deregulationists,* as cleverly described by T. Wu [41]. *Openists* invoke the principles of e2e (and the subsequent openness to innovation) and neutrality (the Internet original practice not to discriminate between uses and content) to require regulation which mandates all broadband network operators to respect open access and network neutrality [42]. *Deregulationists* put forth the Internet failure to provide real-time services (through variable *Quality-of-Service* deployment) and invoke industry "sunk-costs" (preceding any innovation in network service offerings) that need to be recuperated, as arguments against "inefficient" and "long-lasting" government intervention. Naturally, they ask for more space to private network owners. They expect network providers to fund, therefore, Internet evolution and drive the next-generation Internet [43, 44].

These issues are not easy for us in Europe to recognize and fully understand their implications. Several economic and societal subjects profile against the sky of this conflict: i) ethical concerns: the Internet should remain free of any control, from government, business or other; ii) public interest motivations: the Internet should continue to function as *innovation commons,* in the same trajectory of an application-independent data carriage service that allows for the introduction of new applications and eases integration of new technologies; iii) strategies for influencing industry structure: if the Internet is to serve applications requiring "enhanced network performance" (with real-time voice and video features or multicast), and supply efficient broadband access, providers will inevitably deploy vertical integration moves (the bundling together of infrastructure and high-level services or the bundling of broadband access with content); iv) consumer welfare preoccupations: if vertical integration is somehow inevitable, a certain consumer choice over the "routing provider" should be allowed (as it happens in long-distance telephony markets).

Whatever the outcome of this debate would be, one thing is already clear: the business strategies of the network (and network equipment) providers should therefore reflect more on the future of the Internet design. In coming Internet generations, innovation would be introduced from both sides: from the "edge" where the "knowledge of the many" produces new applications and from the "core" of the Internet – and the club of (big) ISPs that "own" that core and want to "organize" its performance in delivering *network service* and, furthermore, to strategically act on the pace and direction of technological change. As R. Nelson points out, technologies and *institutions* evolve together [45]. Institutions are the "rules of the game" [46], and the rules of the game are going to change since applications, becoming more sophisticated and portable, want now to enjoy better network performance.

The current Internet has certainly produced very robust applications, perhaps because applications' designers had to deal with a network with "weak semantics", so they had to "fix up" at the edge problems caused by varying network performance (due to non-mechanisms for making explicit commitments about performance). But as the Internet matures, applications need a different set of operating conditions, more predictable and reliable than the original “best effort” model can provide. Naturally, the new strategies of the network providers (i.e. the “club” of ISPs) reflect the opportunities provided by this institutional matrix. They want to get involved in the applications provision, with the objective to offer enhanced services, and they want to do that in the direction they understand: by increasing the intelligence “in” the network [47].

The fact that the Internet will acquire increasing choice-making maturity over applications delivery is somehow inevitable. It might be a “positive-sum” evolution provided that the Internet will stay open and transparent for new applications. Innovation from the “core” might be a definitive step towards the “horizontal integration model”[39]. It should also be a clear conformation of the dynamics of *open flexible specialization* trajectory, where both are potentially infinite: the set of variable design features (in occurrence, and the design of applications and the design of *network service* to applications) and the domain over which each variable ranges. If this trajectory has to be continued, there is much to be done towards more flexible organizational and productive structures that can provide markets with more customized products, competing on the basis of both applications' quality and variety. In contrast, staying much longer with the packet-design currently used in the Internet, this could challenge the stability of this trajectory and possibly force a movement “out” to a *closed flexible specialization* model for the Internet where: i) minimal and ever-precise network semantics might work towards optimizing current applications implementation; ii) higher performance and greater efficiency for existing applications would prevail over effectiveness in terms of flexibility and evolvability [47, 48].

In a larger sense, *coordination by a new design,* and maybe *beyond design* (through an appropriate co-ordination framework that rationally distribute revenues across Internet players, rewarding the real contribution of each player in industry value chain) is now the challenge. The principles of a new design should be embodied in a reformed Internet architecture that will be able to respond to the changes of the today's world, as described above, while remaining sufficiently open and flexible to incorporate tomorrow's changes. A group of researchers led by MIT Senior Researcher D. Clark (one of the Internet “fathers”) has been working, these last years, in the direction of “*architectured action to preserve the ability (of the Internet) to change, evolve and advance the technology”* [47, 48][40]. Beyond *design for change,* three important concepts appear to be the “tenets” that should differentiate next-generation(s) Internet from the current architecture [ibid]:

- *controlled transparency* (implying the emergence of trust-regulated areas of Internet),
- *isolation of conflicts of interest* (“design for tussle”),
- the *use of a shared, evolvable, soft state support subsystem* (as a compromise between the *stateless connectionless datagram* valuable heritage and the challenge of implementing some part of the applications functionality “in” the network).

[39] See *supra.*

[40] See in this regard the *NewArch Project* on which this document reports when discussing in more detail network design novel architectures for the Internet.

What will finally prevail as a new Internet architecture is the interplay between ecologies of new designs and visions and strategies from network and application providers. In this context, as D. Clark and M. Blumenthal indicate, *"… it is premature to predict the final form. What we can do now is push in ways that tend toward certain outcomes" [39].* Then, there is room for research. What the long-term research can do is to provide the framework for stimulating both architectural innovation and coordination *beyond design,* with stability and flexibility, within such a complex and continuously evolving space as the Internet is.

2.4.2.4. Digital networks

If Internet is the "cause", i.e. the engine for easy-to-implement novel applications, the structural transformation of the economy and social life is the effect. The Internet and its networked applications "host" more and more of the economic and social activity which is being transformed to networked activity. B. Arthur [49] describes this invasion of the economy from the Internet as a neurological process: *"Digital technology is reaching into lots of business and technical processes, and becoming an integral part of them. Businesses and technologies themselves are engaged in ongoing conversations… In other words, digitization is becoming a neurological process in industry itself. And therefore, when the economy comes back, and even before it comes back, this process will continue apace, and industries will discover new functionalities and transform themselves. It's unstoppable".* These digital networks, by connecting (in a unprecedented way) systems, processes and functions within and among companies, between business and customers, and among customers, as well as between governments, citizens, educational, social and professional communities and so forth, become the real edge users of the Internet. If the Internet is somehow coordinated by design, how do these networks combine technology with organizational/social innovations? And then, how do the dynamics of the formation of digital networks frame the positions of their individual parts (business, consumers)?

3. SWOT Analysis

Strengths

- Political ambition to set a coherent agenda to support ICT-based economic growth
- Traditionally strong positioning in many communications industries
- Political and societal awareness of the multiple benefits linked to R&D investments in ICTs
- Perspectives for increasing R&D budgets in ICTs
- Long-term research "culture" and already established tradition of collaboration between industry and academia, created and sustained by R&D Framework Programmes
- Public investments in academic-research networks infrastructures
- Awareness of "convergent technologies" approaches and methods
- Liberalized national markets in communication networks and successful (continuous) implementation of single market policies

- Consumer welfare policies promoting affordable broadband communication services and innovation-encouraging policies for public services (e-government, e-health etc.)
- European telecom operators and equipment manufacturers with global dynamics and healthy financial positions
- Spreading open-source technologies communities
- European success-stories appear (Skype)

Weaknesses

- Research policy implementation problems (it misses a clear framework for evaluating the efficiency of European R&D investments in ISTs / "historical amnesia" or no "lessons from failures")
- The "digital divide" among European countries that sustain essential differences in the available communication network and services to citizens, enterprises and public organizations
- (Rather) near-term strategic research agendas in communications technologies and networks, as defined through Framework Programmes (non-equilibrated balance between market-driven and long-term research within Framework Programmes)
- Increasing electromagnetic pollution (and privacy) concerns among citizens
- (Still) fragmented academia research
- Lack of successful interdisciplinary demonstration projects
- Mediocre "absorptive capacity" as far as it concerns Internet transformations and weak positions in middleware / applications areas
- The excessive weight of telecom operators in network development (local authorities and public-interest organizations are not encouraged enough to build their own networks to serve targeted needs)
- Non-equilibrated balance between large telecom operators and small innovative, applications-oriented, firms

Opportunities

- Compared to the US and other G7 members, the EU has more "technology-push" and "market-pull" available coordination mechanisms to set effective priorities in communications research
- Possibilities of harmonic co-existence between market-driven and long-term, "commons-based", research policies

Threats

- Continuous shift of the "value" from "low layers" technologies to applications, services and digital networks where EU possesses rather weak positions
- Continuous Internet transformations create de facto situations of "disruptive change"

The previous lines summarize the results of a SWOT analysis, showing Europe's current strengths and opportunities as well as weaknesses and threats that challenge Europe. The major *threats* are associated with the complexity of the Internet and its immense potential for continuous transformation that creates de facto situations of "disruptive change". This is combined with a structural weakness EU (at least a part of it) seems to develop a rather limited "absorptive learning capacity" [41] with respect to the Internet evolution paths[42]. As a result, EU risks, somehow, missing again the direction of change and losing further ground in the upcoming re-distribution of positions.

Future *opportunities* are closely related with making full use of diversified set-up for "technology-push" and "market-pull" policies, including new industrial policies. In this context, a potential remedy to improve "absorptive learning capacity" may come from the increase of R&D investments, especially in long-term and effective research priorities. A new more balanced strategy between *appropriability-oriented* and *long-term research* can, in fact, offer the tools to confront these challenges head on. This report wants to contribute by proposing a concise synopsis of six broad areas where long-term research will be key to understanding and framing emerging "disruptive change" trends in the communications technologies and networks sector.

4. Vision-Building for Research Agenda

The present section covers the core contributions of this report. In line with a parallel report on Information Technology (IT) futures[43], we project now the current state of the art and emerging trends into the next 10 years. Continuing on the analysis of the evolutionary dynamics of the communications industry, which was the object of the previous sections, we identify key areas for long-term research. They reflect a vision on the major opportunities for growth in this sector and offer a "converging technologies" research perspective [51] to "make sense" in the future developments surrounding the evolution of communications technologies and networks.

The report details six key areas.

The first two areas are related to research in the critical components (infrastructure technologies and applications) of the Information Infrastructure.

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[41] W. Cohen and D. Levinthan [50] have introduced the concept of "absorptive learning capacity" to indicate a firm's ability to value, assimilate, and apply new knowledge. It is studied on multiple levels of organization (group, firm, and macro-level) and expresses itself as innovation performance, aspiration level, and organizational learning. Antecedents are prior-based knowledge (knowledge stocks and knowledge flows) as well as communication. As *Wikipedia* notices, the theory bases involve organizational learning, industrial economics, the resource-based view of the firm and dynamic capabilities approaches.

[42] This is most likely a heritage from an early perplexity with regard to the effectiveness of Internet *stateless connectionless datagrams* to provide reasonable network service, that of the kind *"ignore it… then surprise… finally accept"* – to quote E. Bohlin from Chalmers University.

[43] W. Bibel's report (see footnote 6).

The next four areas are defined on the basis of more complex challenges, such as design architectures and theoretical models for decentralized networks, complexity management for new forms of digital organizations that leverage the potential of "commons" and open-policy making – where interdisciplinary research needs to make crucial contributions.

1. Enabling infrastructure technologies and technologies for security
2. Applications (focusing on real time and organizations-wide applications)
3. Network design and novel architectures for the Internet
4. Models for understanding the networks of today and tomorrow
5. Cyberinfrastructure, digital networks and information economies
6. The triangle Internet, Mobile, Wireless (or beyond "beyond-3G").

- Enabling infrastructure technologies and technologies for security: this area covers the technologies that support next generations of infrastructure substrates (towards limitless fiber transport capacity), protect network integrity and enable the extension of the communications infrastructure with new branches and topologies and. These include:
  - i) Technologies for increasing network substrates' capacity (optical networking) and for improving over quality with implementing new designs for broadband networks (lambda-based network)
  - ii) Technologies and architectures for last-mile broadband
  - iii) Critical components for enhances mobile and wireless and networks
  - iv) Embedded networks
  - v) Protection of physical infrastructures, security of network integrity (protection from intrusion and hostile attacks), interoperability of information security functions in networks and information systems, network solutions for dealing with emergency situations.

- Applications (focusing on real time and organizations-wide applications): long-term research in this regard should strengthen the quality and the vitality of European basis for producing novel applications. It should foster inter-operation between software development, development methodologies and other non-technical issues (context of applications use and diffusion strategies) and by exploiting industrial policies stimulating innovation. Possible examples of applications with a likely high potential in the next 10 years include:
  - i) Real time applications (voice and video) over IP
  - ii) Messaging and presence
  - iii) Enterprise networked applications
  - iv) Applications for privacy enhancing.

- Network design and novel architectures for the Internet: research in this area is motivated by the limitations of the current Internet with respect to its architectural design. In the perspective of the next 10 years, this research should aim at: i) revitalizing the Internet with a new architecture corresponding to its changing nature and, ii) developing packet-switching networks with performance characteristics and adapting behaviors to the particular needs of applications and network users, iii) designing the efficient interoperation of the Internet with the expanding mobile infrastructure and with networks with different topologies such as wireless and ad hoc networks. This area can be seen as the most strategic area for the whole communications industry, since it relates to an "equilibrate" re-investment of *network intelligence* at both, the "edge" and the "core" of the network. Future network generations (with re-allocated "intelligence" among the parts of the network) are being now designed not only to provide greater network capacity and application diversity, but also to allow for a sophisticated behavior (based on learning from the network events, as they progress, to improve future performance) and enhanced network management functionality (automatic and reliable diagnosis of existing problems, network self-management etc.). "Converging technologies" methodologies, from cognitive networking to bio-inspired communications, are being employed in this endeavor.

- Modeling and understanding the networks of today and tomorrow: the Internet, the Web, and the various networks "living" on them (from the P2P networks to "consumer feedback networks") are complex systems that need to be modeled in order to be understood and efficiently designed. The last few years have witnessed an important research activity devoted to the measurement, modeling and understanding of the dynamic behavior of the Internet and the Web. Research in this area has started with the study of traffic data collected from the Internet and the Web, but it has quickly extended to a variety of attempts to discover, behind these data, regularities and clear patterns (as their "scale free" nature) that can be expressed in mathematical and statistical forms. Researchers now pursuing evolutionary paths and macroscopic properties and behaviors of the Internet and the Web and they shift their focus to modeling the growth and evolution of these networks as a cumulative and self-organized process. They also turn to a very interdisciplinary methodology, calling to various scientific approaches, from statistical physics to complex systems and organizational economics. The ultimate goal is to create network models that are statistically indistinguishable from the real Internet and the Web. This approach that wants to blur the frontiers between the artifact and the model, promises to be very fertile in understanding the dynamics of current complex networks, explaining growth patterns and assessing the stability of their organization and the performance of the service they provide.

- Cyberinfrastructure, digital networks and information economies: research in the design architecture of the communications networks, and in the dynamic properties of their behavior, should be combined with interdisciplinary research with respect to the digital networks and the information economies. These novel forms of organization are enabled by the interoperation between infrastructures, applications and various (overlaying) business and consumer networks. But how these digital networks do organize in space? How do they frame the strategies of the sellers and the attitudes of the consumers? How can they be efficiently managed? Information economies allows for consumers to efficiently obtain product information in a variety of ways: i) through online search (different from search in the physical world which is limited in price discovery and product quality appreciation) which provides "product experience"; ii) by obtaining "personalized" advertising through web and mobile marketing; iii) as a by-product of various online activities ("slashdot-ing", participation in online forums and conversations etc.). What about then the consequences of a dramatic increase in the available commercial information (especially of the information available prior to any product purchase), that is becoming a strong determinant of the purchase behavior? A vision of the structural characteristics of the emerging information economies needs to be articulated and disseminated, to help European enterprises to develop healthy and sustainable business models and strategies for "competitive advantage" in a knowledge economy.

- The triangle Internet, Mobile, Wireless (or beyond "beyond-3G"): mobile networks enter now a new phase of growth enabling much greater intelligence and flexibility to be built into transmitters and receivers (so as to use spectrum more efficiently), *rich applications* and high bandwidth IP multimedia service delivery and ad-hoc networking between smart nodes (devices)[44]. Moreover, European Commission and many other governments in the world are elaborating plans for spectrum reform in a climate of: i) growing spectrum demand and innovative "problem-solving activity" towards more efficient management of spectrum, ii) convergence between mobile and wireless, as well as between fixed Internet and mobile-wireless Internet. In brief, "disruptive" technology change is ahead. Research with diversity in targets and approaches, and systematic experimentation with new technology concepts and regulatory approaches, is the best response to technology uncertainty and the way for Europe to sustain its leadership in mobile technologies, established through GSM. But how far beyond 3G/4G environments should this experimentation go?

The first two key research areas recommended by this report, "Enabling infrastructure technologies and technologies for security" and "Applications (focusing on real time and organizations-wide applications)", are well addressed within the current R&D (within *Next Generation Internet*[45] and *Ambient Intelligence* visions[46,47], as implemented by various initiatives of INFSO/D[48]) – now re-designed, at various levels, in the perspective of 7FP[49]. How could the balance, in these areas, be better configured between market-driven and long-term research, goes beyond the objective of this report and requires a detailed policy analysis and evaluation of AmI and NGI scope and results.

The next four key research areas embrace themes which are possibly addressed in the context of various existing or upcoming initiatives but in this report they are considered as independent

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[44] We report here on a recent ESTO-IPTS report on "The Future of Mobile Commuinications in the EU: Assessing the potential of 4G" which intelligently summarizes the factors that could have, for the foreseeable future, a significant impact on the deployment of mobile and wireless technologies – see: reference [52].
[45] AmI (see footnote 8).
[46] NGI (see footnote 9).
[47] For the security aspects of the AmI paradigm, see: https://rami.jrc.it/
[48] INFSO/UnitD: Network and Communications Technologies
[49] See: EC, Proposal for a Decision of the European Parliament and of the Council concerning the Seventh Framework Programme of the European Community for research, technological development and demonstration activities (2007 to 2013), COM(2005) 119 final

collections of open research questions. These areas challenge our current capabilities in the sense that all of them are related to what C. Papadimitriou [21] calls the "socio-economic complexity" of the Internet: the co-existence in a modular system of various, numerous, elements (essentially networked structures), with diverse objectives and heterogeneous, operated and used by a multitude of diverse economic interests collaborating and competing each other[50]. Learning how to design and manage the coordination and evolution of these structures is critical because it leads to better ways to use these systems. But this will certainly require the development of new forms of understanding, novel methodologies and tools at the edge of what might be scientifically possible and so on. This report recommends three particular *basic research challenges* that might be important sources of innovation in this endeavor and also sources of multiple externalities: *design architectures, network theories* and *interdisciplinary methods.* Briefly discussed in a previous section, we now present them in detail:

- Design architectures: architecture is an essential element of any communication system. It provides a set of abstract organizing principles and structuring relationships among the network's components (algorithms and protocols), that guide the technical design of the network [19]. This is essentially a "reference model" permitting efficient conversation between components and modular construction and development. In this sense, architecture organizes the search for new designs: *"Just as physical architectures both create and constrain opportunities for movement in physical spaces, design architectures create and constrain opportunities in the "design spaces" wherein the search for new and better designs take place. Because they organize the search for new designs, design architectures are an important source of innovation, economic value and consumer welfare in a knowledge-based economy. But, despite their pervasive influence, such architectures are not much discussed…" [18].*

- Network theories: large-scale communications networks with complex architectures, such as the Internet and the Web, are very new, far more optimal, constrained by history and sustained by open-ended "ecologies of hypotheses" that converge to dynamic coordination models, generating very specific structure and robust performance. Appreciative and formal theorizing are required to study fundamentals aspects of complexity in these networks, to improve on their performance [20, 53].

- Interdisciplinary methods: advancements in the above directions need to be supported by a real interdisciplinary research involving transfer of knowledge and modeling techniques from other disciplines to communications research. As suggested in the FET community report [17], *"understanding how such large and highly dynamical networks can be managed requires an interdisciplinary approach, adopting metaphors from economics, for example, as one might define the total network "welfare" as some global measure of the information "well being" of all autonomous systems..".* In our view, we do need not only metaphors and not only from economics: cognitive science, social cognitive neuroscience, neuroeconomics,

[50] See also previous sub-section: "The need for EU to set long-term but effective research priorities in communications".

behavioral and social sciences, all have to offer methodologies and models in next generations of communications technologies and networks.

In the following table, we relate the proposed *four key research areas* to these *three basic research challenges:*

	Design architectures	Network theories	Interdisciplinary methods
Network design and novel architectures for the Internet	Yes		Computer science & Engineering, Cognitive models and biologically-inspired approaches
Models for understanding the networks of today and tomorrow		Yes	Computer science, Economic models, Behavioral models
Cyberinfrastructure, digital networks and information economies		Yes	Computer science, Insights from social cognitive neurobiology and neuroeconomics, Organizational sciences approaches, Economic and behavioral models
The triangle Internet, Mobile, Wireless (or beyond "beyond-3G").	Yes	Yes	Computer science & engineering, Regulation policy analysis and design, Economic models, Organizational sciences approaches

A final notice: We have sought to identify realistic long-term priorities in the communications sector, focusing 10 years ahead, on the basis of two criteria: i) to strengthen our scientific understanding of communications technologies and networks and, ii) to provide a coherent framework of experimenting new departures leading to new designs that generate high value. Of course, the list of six key research areas we propose is not exhaustive. We think however that these topical areas certainly "carry-on" interesting open problems that already attract ambitious researchers and explore novel methodologies that get inspiration from the organization of Complex

Systems (CS) and the cognitive sciences revolution and, somehow, "oscillate" between algorithmic theoretical approaches and computational models implemented over large scale simulated systems[51].

In what follows in this document, we review in detail the four recommended key research areas and discuss methodologies that research in these areas might require to explore in depth.

4.1. Network design and novel architectures for the Internet

Basic and high-level applied research relevant to this area responds to the challenge of facing and influencing Internet continuous transformations. It encompasses various aspects of network design and optimization that include application variety and robustness, performance of packet networks, routing and switching effectiveness, signaling and control, interoperation among different modes (Internet packet switching, mobile networks, wireless and ad hoc networks, sensor networks and so on), etc.

As discussed earlier, the current architecture of the Internet is the object of increasing criticism. Albeit the phenomenal success of the Internet and its growing place in our societies, maybe because of this success, various operational problems appear as a result of a gap between the "old" static Internet architecture and the complex requirements progressively arising from the "reality" of the "normal" evolution. To cope with such inconsistencies caused by this gap[52], software engineers and business strategists have been injecting in the "Internet machine" small, many and perhaps inconsistent doses of change, in a short-term understanding of what is really needed. Today's challenge and opportunity require us to think again about, maybe to design from scratch with the experience of ad hoc transformation of the Internet, an overall architecture which can "host" the future of the Internet. As D. Clark et al. point out, *"the challenge facing Internet research and engineering is to recognize and leverage this reality – at minimum to accommodate it: if possible, to use it to strengthen the technical architecture" [47].*

David Clark leads a group of scientists at MIT pursuing research in defining and prototyping a future architecture towards which the Internet can evolve without losing the strength of the initial design (confirmed as *scalable, reliable, evolvable).* Many of the functional features of this architecture have been developed in the context of the *NewArch Project: Future-Generation Internet Architecture*[53], a DARPA-funded (the Defense Advanced Research projects Agency at the Department of Defense). The *NewArch project* has set the objective to propose a *clean-slate* revisitation of the Internet's architecture in response to the emergence of new requirements and craft a creative and consistent synthesis of many new ideas for architectural change "floating around", in these last years, mostly within the academia and the Internet engineering community. It has succeeded, in effect, to propose a blueprint plan to the Internet evolution (includes: requirements

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[51] Our vision is complementary with what a recent report on Complex Systems research that comes from within the FET community, defines as research priorities in the strategic areas of *Complexity Management for the Internet and the Web* [17].

[52] or motivated by the objective to provide very specific ad hoc solutions, to very specific problems – when such problems appear

[53] See: http://www.isi.edu/newarch/

definition, architectural design as well some of the necessary protocols to realize the architecture) that can be a certain basis for an Internet with more commercial, and military, value[54]. Summarizing NewArch results, project researchers explain that their work *"did not lead to rejection of the fundamental nature of the Internet – an application-independent data carriage service based on variable length packets… The basic design is sound, has passed the test of time, and will serve well in the future. We did conclude that many attributes associated with this basic packet service need to be reexamined, including the pure datagram assumption, global addressing, the linkage of location and identity, and universal transparency" [54].*

DARPA supports this kind of vision over the future of the Internet. In a speech given to DARPATech 2004 Symposium, T. Gibson advocates for the need of a "revolutionary" change that should be implemented at the heart of the Internet: *"The packet network paradigm… needs to change… We must absolutely have a mechanism for assigning capabilities to different users that scales to large numbers of devices automatically… Today's networks are stationary and have a static infrastructure … (mobile) nodes should be able to automatically sign on to networks in their vicinity…" [55]*[55]. Assigning capabilities to different users, i.e., the priority of priorities, this certainly relates to the capacity of (the "core" of) the network to recognize what the user is trying to do and behave accordingly. It is again about the role of the network but now seen from an application perspective. This requires from the problem-solving activity to move far from the "old" deterministic approach translating Quality of Service in traffic engineering and "guarantees" applying differently to different classes of service. The new approaches focus on designing *cognitive* mechanisms which can deal with "network failures": i) determining why a communication (among application programs running in end systems) is failing and, ii) reconstituting, from the "end", the state of "failed" communication. The watchword in the new networking jargon is *Knowledge Plane,* and much of the discussion now is about how to inject *cognition* in the Net through implementing a *shared, soft state support subsystem* within the Internet architecture.

The *Knowledge Plane* is the essence of the new architecture defined by the *NewArch project. Knowledge Plane* is a particular response to the increasing needs of applications in improved *network service* without "destroying", according to D. Clark and his colleagues[56], *the transparent data carriage model* "embedded" in the original design of the Internet and principal success factor for Internet's innovative applications [56]. It is a distributed component of the network, implemented as an *independent software layer* that: gathers information from the end-nodes about *what should be happening;* collects information from the "core" of the network *about what is happening;* processes this information so it can *identify emerging communications problems*

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[54] For a detailed overview of the *NewArch* architecture and protocols, see references [19] and [54]. The outline of the necessary changes to make into the current Internet, and the overarching vision of what the future Internet should be and how we will get there, are described in three papers published between 2000 and 2003, see references [39], [47] and [48].

[55] For a very appropriate discussion on DARPA's arguments, and comments and concepts deepening on these lines, see the presentation of E. Gelenbe (Imperial College), "The Cognitive Packet Network", in Dagstuhl Seminar, Cognitive Networks and Radios, October 2004 – see: http://www.dagstuhl.de/04431/

[56] MIT Laboratory for Computer Science (MIT LCS) leads the *Knowledge Plane project* (Funding: DARPA, participate: 11 Labs and Universities, end-horizon: 2010).

(network failures); *initiates conversations* with the user about the nature of these problems; and *corrects* failures while *learning* from past experiences.

Box 5: The Knowledge Plane

D. Clark et al. (http://www.csail.mit.edu/research/abstracts/abstracts04/html/114/114.html.):

"Motivation: What might the knowledge plane be good for? Here are two examples to illustrate.

Example one: When some part of the Internet fails, it is almost impossible for the end user to tell what has happened, to figure out who should be notified, or what to do to correct the fault. Imagine a program (we call it the why program) that a user can run when something about the network or a networked application seems to be broken. The why program starts with a component that runs on an end node, and performs diagnosis when there is a failure. The diagnostics can check out functions at all levels, from packet forwarding to application function.

Once the end node has performed what diagnosis it can, the next stage is for the tool to add assertions to the shared knowledge plane about what it has discovered, and ask the knowledge plane for relevant information. This contribution to the knowledge plane allows all the users on the network collectively to build a global view of network and service status. Using this information, this tool would give the user an explanation of what had gone wrong in terms that are meaningful to the user, and also information to the network operator in his terms. Network operators have the option of adding additional facts to the knowledge plane about known failures; in the ideal, a user who trips over a problem might not just get back diagnostic information, but information from the provider about when the problem will be resolved.

Example two: The dynamic routing of the original Internet did not take into account administrative and policy constraints, so routing today is more and more defined by manually configured policy tables. Static tables and manual configuration make the network brittle to failure, hard to change, and even harder to reason about globally. Imagine a distributed configuration manager for a region of the Internet, which would accept high-level assertions, at the administrative level, about how the components of a network are supposed to arrange themselves, and guide the actual detailed configuration accordingly. Examples include controlling the deployment of a consumer network in the home, an ad hoc network in support of a rapid deployment force, or a network for a small business.

The distributed manager should have enough understanding of low-level configuration to detect if the network is properly configured according to the high-level constraints, to detect if a better configuration alternative is available, and to detect if the system appears to be corrupted. The system must be able to deal with different assertions made by different parties, and either compose them or detect that they are inconsistent. Successful accomplishment of this project could lead to substantial reductions in manpower needed to configure and operate networks.

Previous attempts to do "high-level network management" have not been very successful; one possible reason is that previous projects have not been able to find the correct high-level abstractions. The necessary hypothesis is that there exist suitable ways to abstract detailed behavior, and to talk about goals, plans, constraints and methods at a high level. The knowledge plane is much more than a database of facts-it is a construct that embodies cognitive tools and learning".

The challenge toward developing such *a Knowledge Plane (KP),* separately from (on top of) the existing *planes* (data plane, control plane, management plane) is immense, as so do the practical difficulties to implement the new layer in the Internet architecture. But the idea of developing a cognitive layer (relying over cognitive science and AI achievements rather than traditional algorithmic approaches) to enable self-adapting, self-managing networks, and applications that run on the KP, or *K-apps,* is particularly powerful. "Cognition" can fill the gap between applications and network infrastructures by initiating a "conversation process" between them. As pointed out earlier on, in the initial Internet design, applications and network infrastructures are separated through the IP spanning layer and this separation has leveraged unprecedented innovation opportunities. Now, emergent cognitive networks re-integrate "back" network functionality into applications operating conditions, in a completely new framework that introduces a re-distribution of tasks. Networks can therefore interact with applications to make them more effective. This interaction looks is like a *conversation:* networks understand, and learn, from what applications want to accomplish and applications know how to explore (varying) network capabilities. We have not without reason used the word "conversation" to illustrate the interactive process between applications and network infrastructures implemented by the cognitive network. In other domains too, from automobile to complex information systems for defense and commercial uses, such "dialogical action" supports effective product design and fabrication, when *flexible specialization* models apply[57].

Box 6: DARPA's vision on the cognitive network

C. Ramming [59]: "…Model-based systems have allowed spacecraft to operate in unforeseen circumstances without the need for human intervention. We can exploit these results. But there are also more inherently distributed approaches to explore. One is stigmergy, a biologically inspired concept that exploits the relationship between an agent and its environment. Another is the fertile ground of algorithmic game theory, which can provide mechanisms for understanding how distributed agents will arrive at a stable systemic optimum. We need your ideas about how these existing breakthroughs can be applied to cognitive networks in the short run, and we look for breakthrough ideas as well to enable learning and reasoning about networks and distributed systems. All of these research areas will need to be tied together in a principled architecture for network management: one that applies not just as a point solution to one problem, but as a general new structure that will evolve gracefully as the underlying network does and that will perhaps even apply to more than one kind of network. This architecture and the work of cognitive networking cannot be enabled by any one community today... The cognitive community is absorbing the experience with large-scale distributed systems that is a core competency of the networking community. Conversely, the networking community is absorbing history and experience with learning and reasoning and cognitive architectures. What emerges will be an invisible college that combines the insights of both fields to achieve remarkable new results. In the area of cognitive networking we are staking out goals that intrinsically further our understanding of cognitive techniques. Ultimately we will arrive at general solutions for at least two major aspects of network management—fault management and configuration…".

[57] See footnote 32. For more details, see the recent work from M. Piore [57, 58] on the *integration of components* (i.e. "the last and in many ways least interesting stage in the problem-solving process") in conditions of *radical uncertainty*. Based on cases-studies from various industries, Piore and his colleagues recognize in the integration process the characteristics of an open ended and creative coordination achieved through *conversation*. Conversations between industrial project parties (within and across project teams) in the context of an *interpretive* process, *"generate a framework for action that is like a language…"*.

In Europe, the cognitive network concept also attracts increasing scientific interest[58]. Networks with self-managing, self-adaptive capabilities are understood here under the more generic term of “autonomic communications”. *Autonomic Communications* have been identified as an important area for future research and development from a group of European experts in the context of a consultation on novel communication paradigms for 2020 [60, 61, 62]. Then, a FET call on “Situated and Autonomic Communications has launched by FET (FP6, 4th IST call, Marsh 2005)[59] with the objective *“to promote research in the area of new paradigms for communication/networking systems that can be characterized as situated (i.e. reacting locally on environment and context changes), autonomously controlled, self-organizing, radically distributed, technology independent and scale-free… Consequently, communication/networking should become task- and knowledge-driven and fully scalable”.*

Box 7: Autonomic Communications

Situated and Autonomic Communications (ftp://ftp.cordis.lu/pub/ist/docs/fet/comms-60.pdf):

“Rationale: The recent advances in communication and networking technologies and the way in which these are being integrated in the human, working and social framework have made it evident that there are a number of related technical and socio-economic areas whose understanding is still less than satisfactory, and in which long-term research is needed. In general, it can be observed that the increasingly higher density mesh of components of communications systems and the resulting growing complexity of control requires more and more distributed and self-organising structures, relying on simple and dependable elements able to collaborate to produce sophisticated behaviours. The main feature of future communication paradigms will be the ability to adapt to an evolving situation, where new resources can become available, administrative domains can change and economic models can vary accordingly. The vision is that of a world pervaded by ubiquitous communication facilities, offering their services to the users and capable of self-organizing and self-preserving their functionalities without any direct human intervention. This entails fundamental advances both in the architecture and functionality of the network, and in the characterization and understanding of the common communication medium”.

The projects related to the Autonomic Communication (AC) research area should start in 2005, so it is not possible to evaluate the capacity of the initiative, in practice, to propose an architectural framework for the next-generation Internet (or its wireless and mobile ramifications). It is certainly an issue to see whether AC projects will show an ambition to weigh on the Internet transformations

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[58] Notice in this regard interesting work from the Electrical and Electronic Engineering Department of Imperial College (Intelligent Systems and Networks Group), and particularly from E. Gelenbe. For a more general apprehension of the European cognitive networking community, see the “Cognitive Networks and Radios” Workshop, organized by Dagstuhl (http://www.dagstuhl.de/About/index.en.html) – see also footnote 18. The concept of cognitive network relates to previous work on software / cognitive radio which is now generalized to yield novel networking paradigms.

[59] Future and Emerging Technologies (FET) call on “Situated and Autonomic Communications (COMS) - Communication Paradigms for 2020 (http://www.cordis.lu/ist/fet/comms.htm)

or, targeting larger, will move towards exploring eventual post-Internet network problems[60]. Yet, the debate between *Autonomic Communications* and *Knowledge Plane* approaches has already started and possibilities of convergence appear in the air[61]. What is more certain is that with this initiative, a European "self-adapting network" community will be progressively formed.

Recommendation: The cognitive network, and the design and development of network structures with self-adapting (to Internet applications' needs) capacities, might become a very strong research line in the future. It is expected to be the basic component of the next-generation Internet architecture. Research in the key area of Network design and novel architectures for the Internet, and in particular in the topic of cognitive network and the interaction between networks and applications in a context of self-adapting networks with learning capacities, it is of major importance to the vitality and enhancement of the Internet. Furthermore, research in the architecture of the future Internet is expected to provide strategic support, and leverage cross-fertilization opportunities with existing and future EU research projects in the following strategic areas for network design: *active networking*, *control and management plane, wireless ad hoc networks and sensor networks*, *grids and large-scale distributed networks;* it will finally benefit projects dealing with the critical issue of *interoperation among different modes* in a permanently heterogeneous situation (Internet packet switching, mobile networks, wireless and ad hoc networks, sensor networks and so on)[62].

4.2. Models for understanding the networks of today and tomorrow

Basic and high-level applied research relevant to this area responds to the challenge of measuring and modeling: the Internet; the Web; the growing peer-to-peer and local networks (wireless, ad hoc, sensor networks etc.); the cyber-social networks formed by the users of the Internet's applications. Network measurement and modeling are critical to the understanding of the Internet decentralized organization and multi-layer structure, dynamic behavior and patterns of performance and growth. Evidently, as the Internet becomes an integral part of everyday life, and new uses of the Internet appear (stimulated by the development new applications such as real-time applications, i.e. voice-over-IP, and the convergence of the Internet with mobile and wireless networks), interest in network measurement and modeling techniques expands[63].

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[60] See for example the very divergent views in this regard from I. Stavrakakis and H. Zimmerman at the inauguration meeting of Autonomic Communication Forum (http://www.autonomic-communication-forum.org/im/index.html).

[61] See: 19th International Joint Conference on Artificial Intelligence, Edinburgh, July-August 2005, Workshop on AI and Autonomic Communications: Developing a research agenda for Self-Managing Networks and the Knowledge Plane (http://www.infj.ulst.ac.uk/~acomms/ijcai-05/).

[62] INFSOD1 projects and clusters (http://www.cordis.lu/ist/directorate_d/cnt/proclu/p/projects.htm), GRID Networking Projects (http://www.cordis.lu/ist/rn/grids.htm) and FET's DELIS and EVERGROW projects (http://delis.upb.de/ and http://www,evergrow.org): these are examples of research projects that could benefit from, and contribute to, a long-term research initiative in novel architectures for the Internet.

[63] IEEE Internet Computing has recently published a collection of interesting papers on the techniques practices and upcoming challenges with respect to *Internet Measurement.* For an insight into these papers, see reference [63].

There are obvious scientific reasons motivating the rise of interest for research in this field. The Internet and the World-Wide-Web are archetypal cases of large scale self-organized networks bringing-in *emergent phenomena* and new challenges for modeling networks formation, stability and evolution. One of them bear noting here. The Internet consists of many interdependent parts, mostly *routers* (switches) that direct traffic and subnetworks (or *Autonomous Systems*[64]*)*, and layers, with the central problem being that of "how to get these parts to work together in reasonable performance". This is a coordination problem that involves, at least, two major research issues: i) identify (and explain) cause-effect relationships present in large-scale engineered graph structures and, ii) search for how order (albeit high diversity) in the Internet (and the Web) might be achieved. Network theories and models are the tools to address these questions.

In general terms, network models are very useful: i) in analytical and simulation-based studies network protocols performance (topology in fact sometimes has a major impact on the performance of network protocols) ii) in improving network performance through new algorithms and, iii) in network engineering. Furthermore, knowledge of network behavior could assist practitioners in optimizing the allocation of physical resources, such as application servers, routers, switches and leased lines (network topology can have a major impact on how network protocols work in practice); it also offers tools to the networking community to affront increasing infrastructural pollution, i.e. viruses, worms and spam traffic, and possibly control such network pollution and "frame" attack traffic. A similar rationale applies in the Web too: modeling the Web can provide several insights into the nature of information propagation processes over the Web and give some explanations to the formation of certain structures on the Web[65].

This research is already making an impact on Internet and Web Modeling. Many of the networks providing *connectivity* of individual components *(nodes),* whether they are machines in the Router-level graph, entire subnetworks (Autonomous Systems) in the AS-level graph (which represents

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[64] Each Autonomous System (AS) is a collection of routers and links under a single administrative domain. A university network, a local network, an ISP network form an AS.

[65] In fact, the Web appears to be a very organized space with densely linked *communities* of thematically related web pages and sites [64] that forms a *bowtie-like* composite structure [65]: *"The "knot" of the bowtie, called the SCC (Strongly Connected Component), represents the single giant strongly-connected component. The "left side" of the bowtie, called IN, defined to be all pages not in the SCC, but from which a path exists to some node of the SCC. Since a path to some node of the SCC implies a path to every node of the SCC, a surfer beginning at some page of IN can reach any page of the SCC… Similarly, another large set of pages make up the "right side" of the bowtie. This set is called OUT, and has the property that any page of OUT can be reached from any page of the SCC by following hyperlinks, but no page of the SCC can be reached from a page of OUT by following hyperlinks. A surfer beginning at one of these pages will quickly get stuck and be unable to explore further. One may think of these pages as corporate internets which are well-known, but whose links point only internally. Thus, in this model it is always possible to surf the bowtie from left to right, but not the other way: from the pages of IN a surfer can reach SCC, and can then continue on to the pages of OUT, but motion in the other direction is not possible by clicking on links. Finally, there is a fourth region called the TENDRILS, consisting of pages that do not link to the knot, and which are not reachable from the knot…".*

organizational interconnectivity between subnetworks)[66], or web pages and web sites in the Web level graph, show the so-called *scale-free property [66, 67, 68]*[67]. This implies heavy-tailed distributions in node degree, i.e. nodes with a large number of connections to other elements *(hubs)* through which essentially most traffic must flow. In mathematical terms, these heavy-tailed distributions might conform to *power laws,* that is a particular (degree) distribution where the probability of a chosen node to have exactly *k* links follows $P(k) \sim k^{-\gamma}$, with γ being the degree exponent [67]. *Power law-based* techniques are in sharp contrast to the previous *random network-based* approaches to model complex networks (in a *random network,* the nodes degrees follow a Poisson distribution, which indicates that the vast majority of nodes have the same number of links, approximately equal to the network's average degree – a model that evidently can not explain the topological properties of the Internet and the Web).

Box 8: Network topologies and measures[68]

Network: A network is a set of items called vertices, or sometimes nodes, with connections between them, called edges.

Directed/undirected: An edge is directed if it runs in only one direction and undirected if it runs in both directions. Networks composed of directed edges are themselves called directed graphs.

(Nodes) In-degree: The number of edges pointing to a vertex.

(Nodes) Out-degree: The number of edges starting from a vertex.

Scale-free: Networks with power law-degree distributions; the probability that a node has k links follows $P(k) \sim k^{-\gamma}$, where γ is the degree exponent.

Clustering coefficient or Transitivity: The mean probability that two vertices that are network neighbors of the same other vertex will themselves be neighbors [notice: many real networks exhibiting *scale free* properties show also a large clustering coefficient, and consequently *small world* properties, signature of a composite structure with loosely interconnected but tightly interlinked clusters of nodes].

Hierarchical Network: A network organized into many small, highly connected topologic modules that combine in a hierarchical manner into large, less cohesive units, with their number and degree of clustering following a power law.

The facility to collect data from Internet and Web-related measurements and the discovery of a scale-free regularity have rapidly led to a *first generation of models* aiming to reproduce the evolving structure of the network. They borrow principles and techniques from statistical physics and the self-organized systems. In the most popular of them, the so-called *Barabasi-Albert model*

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[66] The AS graph is somehow the equivalent of a hierarchical transportation network connecting large with small cities, where ISPs-nodes organize in "tiers" and connections between nodes correspond to links along which packets are routed. Notice that this graph is derived from BGP routing tables (while the *Router-level graph* comes from *traceroute* measurements).

[67] According to a part of the literature, the recognition of a topology with hubs is relevant in understanding Internet's robustness to damages but also explains its vulnerability to malicious attacks when targeting these nodes with *high-vertex degree* (the *Achilles' Heel* of the network).

[68] See references [67], [69], [70].

(BA) [67, 71], network structure (scale-free) is considered to be the outcome of an internal growth process with three main facets: i) network expansion through accumulation of vertices – the Internet and the Web evolve, as time goes on, by incrementally adding new nodes and new links to the existing graph structure, ii) *preferential attachment* of new vertices to nodes with an already large number of links *(i.e., high-vertex degree)* – in the sense that the probability that a given vertex receives an edge is proportional to that vertex's accumulated connectivity (or *the rich get richer* phenomenon)[69] and, iii) network rewiring as a "local" process of (randomly) removing links and replacing them by new links[70].

Similarly, to explain another intriguing regularity of the Internet topology, at the level of network traffic this time, i.e., its *self-similar* scaling behavior (that is, roughly, the behavior of a traffic rate[71] process, measured at some time scale on a link of the Internet, is preserved irrespective of scaling in space and time)[72], network traffic models akin to *criticality-based dynamics* have been initially proposed [74, 75].

To sum up, the attribution of scale-free properties to the Internet and the Web means, in essence, that these networks have a "macroscopic" architecture exemplified by a heavy-tailed distribution of connections. But most times, this distribution follows a power law but it is not easy, as explain S. Dorogovtsev and J. Mendes explain [76], to find empirically whether the distribution is exactly of power law or not. For example, there is strong evidence that AS connectivity evolution (AS: Internet subnetworks) based on BA model's rules is inconsistent with empirical AS growth measurements [77]. Of course, any distribution we get from the Internet and the Web shows in fact a *high variability* that needs to be explained. But is this generated by a "microscopic" mechanism such as the preferential attachment?

It is evident that the preferential attachment mechanism, especially as described in later, mathematically more elegant, versions of the BA model [76, 78], yields a connectivity-fueled network growth produced by a self-organized process. Yet, the preferential attachment model fails to account for two very important features of the current information networks:

i) Internet network performance: architectures solely based on the "primitive assumption" of preferential attachment, when implemented experimentally, obtain terrible *performance* that is not of course the case of the real Internet [77, 79].

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[69] A similar mechanism for network growth, named *copying,* is proposed by R. Kumar et al [72]. In this story, some vertices choose their outgoing edges independently at random but other vertices replicate existing linkage patterns by "copying" edges from a randomly chosen vertex.

[70] A "radically" alternative approach to generate power-law graphs, which is rather structural than evolutionary, is proposed by W. Aiello et al [73]. It implies a *random* graph model but with a prescribed *power law degree sequence.*

[71] Number of bytes traversing a given link per time unit.

[72] In fact, empirical results show that Internet traffic is bursty and has fractal behavior over a wide range of timescales.

ii) Web sites fast growth: popular web sites grow quickly; for example, Yahoo!, AOL, Amazon, and eBay have built, as reported by consulting firm Morgan Stanley [80], some of the fastest-growing, most valuable brands in history, achieving that status relatively inexpensively. It is not possible to obtain such fast growth rates for the *nodes* of the network without assuming something more "concrete" than preferential attachment, like behaviors inducing positive feedbacks into the process of web sites competing for market share [81].

To break through the barriers these first generation models pose, to provide closer-to-reality physical explanations for the overall network structure, new considerations have lately appeared: i) produce other metrics than the degree-distribution and, ii) incorporate in the mechanisms of network deployment and growth technology and economic constraints [82] and perhaps realistic behavioral assumptions to capture the attitudes of the principal stakeholders (ISPs, web sites, consumers). In this endeavor, a *second generation of models* has recently been developed with the objective to reproduce not only the *local properties* of the Internet and Web graph (such as the scaling property) but also to create *in vitro* network topologies that are consistent with the reality and able to provide insight into the large-scale hierarchical structure of the Internet and the Web. Even though this modeling direction does not come from within the network scientific community formed around the BA model, it is somehow reflected on more recent visions of this community. In a "virtual round table" that started during a Conference of experts in Rome in 2003[73], it has been recognized that the network provides only the substrate on top of which the dynamic behavior of a system must unfold: *"Dynamics, traffic and the underlying topology are therefore mutually correlated and it is very important to define appropriate quantities and measures capable of capturing how all these ingredients participate in the formation of complex networks" [53].*

To be more precise, these new approaches are rather pursuing the objective of modeling complex structures in terms of trade-offs between system-specific objectives and constraints, that is based on the principles of the *HOT class of models* (Highly Optimized Tolerance or Tradeoffs) [20]. In a HOT-inspired context, a new model, the so-called *FKP model* [83], proposes a (random) tree generation model which grows incrementally in the sense that every new node is connected to a pre-existing node so that can minimize a trade-off between cost and efficiency (in that way nodes that have early arrived are more likely to obtain small hop cost and high degree). Applied into the Internet graph, this model seems to obtain fairly good results that prove the relevance of such a multi-criteria optimization in explaining heavy-tailed Internet distributions [84].

Furthermore, another network model *(HOTnet)* [82] applying at the Router-level graph of the Internet, based as well on the HOT approach and built to incorporate the tradeoffs between router capacities and ISPs' economic considerations in the design process, succeeds to achieve network

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[73] Among the scientists participating to the discussion have been: A. Barrat (Univ. Paris-Sud), A.L. Barabasi (University of Notre Dame), G. Caldarelli (Universita La Sapienza), P. De Los Rios (Ecole Polytechnique Federale de Lausane), A. Erzan (Istanbul Technical University), B. Kahng (University of California, San Diego), R. Mantegna (University of Palermo), J.F.F. Mendes (Universidade de Aveiro), R. Pastor-Satorras (Universitat Politecnica de Catalunya), A. Vespignani (Orsay).

performance characteristics and efficiency close to the real Internet metrics (that BA-based topologies could not deliver). At the same time, this model is able to provide an insight into the reasons behind the physical heterogeneity of the Internet nodes, made up by two different groups of routers: low degree routes placed at high speed nodes *(core)* and high degree routers located in low-speed nodes *(edge).*

Box 9: Highly Optimized Tolerance or Trade-offs (HOT)

J. M. Carlson and J. Doyle [20]: The concept of HOT was introduced to focus attention on the following issues: "*Tolerance* emphasizes that robustness in complex systems is a constrained and limited quantity that must be carefully managed and protected. *Highly optimized* emphasizes that this is achieved by highly structured, rare, non-generic configurations that are products either of deliberate design or evolution. The characteristics of HOT systems are high performance, highly structured internal complexity, and apparently simple and robust external behavior, with the risk of hopefully rare but potentially catastrophic cascading failure events initiated by possibly quite small perturbations".

In the near future, these two different research approaches (i.e. "self-organized criticality" and "organized complexity") applying into modeling the Internet, the Web, the information networks in general, will augment their heuristic and experimental methods and tools with more theoretical-rich insights – and maybe someday converge to accept that information networks can be at the mercy of both *emergence* and *organization* forces. For the moment, research carefully focuses on the drivers of network deployment and growth. As Li et al. [82] point out, *"in the absence of an understanding of the drivers of network deployment and growth, it is difficult to identify the causal forces affecting large-scale network properties and even more difficult to predict future trends in network evolution".*

Finally, these two approaches for modeling the complexity of information networks do not exhaust the ways in which our theories can be employed to understand and uncover the "most significant" drivers of evolution. Novel concepts appear to improve the characterization and understanding of the emerging networked structures, as for example the concept of *weighted evolving networks*[74]. Besides, *social networks* structures are being added, as additional layers, to our modeling artifacts. There is recently an apple inquiry, among scientists, on the influence that may have in the organizations of the Web and the Internet, the social networks of Internet users [86]. Scientists discover that emergent social process of online authorship, as exemplified by the *blog* phenomenon, and strong community relationships (such as *instant messaging buddies)* developed within increasingly larger groups of *weakly-connected* Internet users, might have a significant impact on the evolution of Web topology.

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[74] As reported by A. Barrat et al [85], weighted models consider not only the topological structure but take also into account the interaction strength – the weight of the link – that characterizes real networks: *"interestingly, recent studies have shown that weighted networks exhibit additional complex properties such as broad distributions and nontrivial correlations of weights that do not find an explanation just in terms of the underlying topological structure".*

Recommendation: Real data as well as the models aiming to explain the structure and evolution of the information networks, are useful not only to researchers but also to traffic and security engineers and to ISPs and telecom operators. Research in the key area of Models for understanding the networks of today and tomorrow (the Internet, the Web, the peer-to-peer networks, the local wireless, ad-hoc and sensor networks, and of course the mobile network) has the promise to uncover the "most significant" drivers of topology evolution. This increases our knowledge on designing network architectures and protocols that deliver improved network performance and usability. The field of network modeling is still a discipline in its infancy, but it holds a critical key for the evolution of the infrastructure of the Information Society. There is in Europe a strong base in science and technology areas of relevance for modeling the information networks[75]. It should be supported to grow more rapidly. However, real scientific achievements will come only from the continuous iteration between measurement, modeling and analysis. So, a more interdisciplinary work is necessary and incentives should be provided to the interaction between the communities of network theorists and network engineers and economists. Furthermore, compared to the USA, Europe has good opportunities to make use of cross-institutional cooperation and targeted measures to develop measurement technologies and large scale test-bed projects to address measurement needs. The technologically advanced European academic networks could have a major involvement in this regard and play a vital role in the provision of data, the diffusion of research and in the building of a community of researchers.

4.3. Cyberinfrastructure, digital networks and information economies

Basic and high-level applied research relevant to this area could contribute to the development of better cyberinfrastructure and foster the development of digital networks and new types of knowledge-based organizations. "Cyberinfrastructure" [76] is the *coordinated aggregate* of connectivity, software, hardware and "convergent technologies", required to support current and future economic, cultural and social activities within the *network society,* as it is defined by M. Castells [88] and others. Cyberinfrastructure provides a variety of artifacts that include: appliances and high powered computers; storage-mining and visualization facilities; sensing, observing and controlling technologies; online value chain management and customer relationships management applications; inter-personal content management, collaboration and deliberation tools and so on.

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[75] Numerous universities and research centers have developed activities in the field of Internet, Web and mobile networks modeling. FET has, in the past, supported research in the area of Networks Growth and Evolution through COSIN FET OPEN project (http://www.cosi.org) and, more recently, through DELIS and EVERGROW projects (see footnote 62).

[76] The term has been proposed by a NSF Workshop (NSF Workshop on Cyberinfrastructure for the Social Sciences) to design *"a comprehensive digital environment that become interactive and functionally complete for research communities in terms of people (expertise, knowledge), data, information, tools, and instruments that operate at unprecedented levels of computational, storage and data transfer capacity"* (whose facilities would support current and future discoveries in science and engineering). Such a vision can be expanded to include not only research networks but all the *digital networks* that constitute the texture of the emerging Information Society and shape today and tomorrow economies and societies. These digital networks appropriate and modify the Internet and the other IT technologies to transform *production*, *consumption* and *experience* relationships consistent to the requirements of the Information Age. For more details on cyberinfrastructure, see: http://vis.sdsc.edu/sbe/ and reference [87].

They enable and support the wide spread of *digital networks* and prop up their prevalence as the organizational form of the new digital economy.

Digital technology is now fundamentally reaching into economic and social processes to become an integral part of them [89, 90]. At the level of production-exchange, digital networks are increasingly taking over localized physical markets and physical inter-exchanges. They promise to deliver productivity and growth as efficient "carriers" of *conversations* between systems, process and functions within and among companies and between business and customers. Examples of business digital networks include: business-to-business and e-marketing networks (supply-side), outsourcing networks, web auctions networks, consumer feedback networks (demand side) etc. On the other side, the emerging peer-to-peer and inter-personal information networks (as exemplified by the Gnutella and Slashdot phenomena) overlay onto the existing human social networks, to offer them more interactivity and exposure and opportunities for influencing each other. Besides, new forms of networks, appearing as *communities of blogs* (where everybody's blog within the community provides incrementally links to and comments on others' content), create novel, original forms of individual expression and (public) horizontal communication. Obviously, digital networks correspond to the increasing needs of the economy to manage flexibility by combining coordinated decision-making and decentralized execution, while allowing for open communication and more freedom of speech in society, as well as for ad hoc but pervasive collaboration [89][77].

When looking at the process of organizational implementation of the digital networks from the inside, however, one can see that various inefficiencies are still substantial. The first problem in realizing these new organizational structures, is that the new *network model* is not wholly coherent internally or fully consistent with the social and economic environment. One of the common complaints relates to high failure rates of IT projects, especially of e-business projects[78]. Besides, the debate is very recent about the actual effectiveness of IT investments that a book under the title "Does IT matter?" has initiated [92][79]. In spite of several breakthroughs on the cyberinfrastructure front, the dynamics of the digital networks are not properly understood beyond the realm of their strictly technological aspects. This is perhaps what P. David argues about when saying that *"the supposedly 'softer parts', that is to say, the socio-institutional elements are necessary complements of the technical components in the new digital information infrastructure that would support collaborative activities of many kinds" [93].*

[77] More specific overviews of how processes for creating and organizing network-based knowledge interact with information technology, business strategy, and changing social and economic condition, see the Conference "Advancing Knowledge and the Knowledge Economy", organized in January 2005, in Washington DC, by several international organizations (among them, EC Research Directorate-General and OECD) – see: http://www.advancingknowledge.com/index.htm.

[78] The trade press and the reports of the consulting companies report on a high percentage of network-enabling projects, such as CRM (Customer Relationship Management) and SCM (Supply Chain Management) projects, thatbfail to meet their objectives. Maybe this situation is positively changing these last days [91].

[79] See also: http://www.nicholasgcarr.com/doesitmatter.html

So, applying research in organizational sciences to digital networks might create a framework to face the uncertainties that impede the leverage of the transformative opportunities of the digital networks and foster the development of *networked* and *virtual* organizations. But this clearly requires a very interdisciplinary research program that should go beyond current technology-centric research approaches to motivate the real formation of *communities of meaning* between engineers, computers scientists, organizational scientists, sociologists and economists, as well as cognitive and behavioral scientists – whereas technical universities and research centers should be given incentives to collaborate with business schools and social and behavioral sciences university departments.

Of course, digital networks would never be possible without the emergence of a cyberinfrastructure and it will not be efficient in terms of ever increasing flexibility and adaptation if this cyberinfrastructure does not evolve with massive investments forward. This is another major research program that obtains a large consensus, in Europe and in the US as well[80], at least at two levels. First, cyberinfrastructure needs to be constantly augmented to support new modes of data analysis, data comparison advanced techniques, smart visualization engines, communication and collaboration tools and so on. Second, science (including social and behavioral disciplines) can be the "laboratory of innovation" to build new types of digital networks with large scale *sharing* capacities (as in the vision of Grid networks), or with advanced information organization efficiencies to support scientific information publishing and knowledge communities (i.e., online searchable information databases with incorporated tools for analyzing data); and to sustain *always-on* group organization forms, with smart engines able to manage *instant presence* and *role-based* levels of enhanced interaction between individuals and groups of individuals.

We conclude our analysis with the key suggestion that research on business and science digital networks, and cyberinfrastructure enabled forms of organizations (networked and virtual organizations), should continue to be supported[81] and oriented towards novel interdisciplinary lines:

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[80] An updated version of European visions on the cyberinfrastructure (as a "knowledge empowering environment") is provided by the e-Infrastructure Research Group in the document "e-Infrastructures Opportunities List" (available at: http://www.e-irg.org/meetings/2005-roadmap/OpportunitiesList.pdf) – see: reference [94]. For a short summary of European initiatives in this regard, covering FP5, FP6 and nationally funded projects, see: Grid Today (April 2005), W. Gentzsch, "Grid Computing: How Europe is Leading the Pack" (available at: http://news.taborcommunications.com/msgget.jsp?mid=366726&xsl=story.xsl). With respect to the US position in the subject, which is strongly oriented towards "an interdisciplinary not just multidisciplinary research", see: Atkins Report of the NSF Blue Ribbon Advisory Panel on Cyberinfrastructure (http://www.communitytechnology.org/nsf_ci_report/) – see: reference [95] – and the Final Report of the NSF Workshop on the Cyberinfrastructure and the Social Sciences [87].

[81] Virtual organisations and collaboration environments have been addressed via the FP6 Strategic Objectives concerned with "Application and Services for the Mobile User and Worker", "Networked business and governments", "eLearning and Cultural Heritage" and "Products and services engineering 2010".

i) To generate taxonomies of innovative organizational models (at various levels, firm, public administration and government services, political and civil society movements) that are most likely to emerge from the overlay of the digital networks onto the economic, cultural and social life.

ii) To discuss governance issues in digital networks and elucidate technical and organizational frameworks which prove to be effective and useful to participants.

iii) To evaluate "risks" associated with extensive sharing of information among participants in digital networks, maybe beyond their own "information strategies" (information leakage)[82], and examine the impact of "leakage" on to incentives to participate in these networks.

iv) (Based on the above) To model the structure and evolution of digital networks[83], possibly with the application of computational techniques (see below).

Box 10: Internet P2P communities

B. Buchanan and R. Dum [17]: "As the functioning of P2P networks and the relationship between autonomous systems illustrates, the Internet is a novel setting for the emergence of new socio-technological communities of many kinds. Trying to encourage cooperation in such communities is one key goal, but so is the fundamental characterization of the structure and evolution of such networks, ranging from weblogs and distributed encyclopaedias (such as Wikipedia), to large and authoritative sources of scientific literature. These and many other web-based resources implicitly define and create social networks of users, who produce, share and disseminate information in totally new ways, with human behaviour and technological development tightly intertwined. Detecting such communities is a key goal. The term "community" indicates here a subset of agents that are topologically more connected with each other than with the rest of the network, regardless the semantic content associated with the agent. The identification of topological communities is a crucial issue also for the investigation of the effect of topology on communication and assimilation processes, i. e. the emergence, out of an initial heterogeneous situation, of groups of agents sharing the same semantic content. Several models of assimilation processes (diffusion of culture, norms, beliefs) have been introduced in recent years and their behavior when they evolve on ordered lattices has been thoroughly investigated. A basic scientific goal is to mine the inner structure of these social systems, unearthing the principles that govern their formation. The properties of complex social networks are currently subject to an intense activity, and complexity science aims to tackle a host of fundamental questions. For example, what is the interaction between network structure and communication abilities? How does topology influence the emergence and stability of communication systems? What are the prerequisites, conditions, and consequences of centralized vs distributed communication networks? In this perspective it is highly important to focus on the morphogenesis of the pattern of communications, the self-organization into hierarchical of information, and the feedback loop between spatial-social organization and emergent communication…".

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[82] K. Anand and M. Goyal [96] use the term "information leakage" to materialize the fact that information, advertently or inadvertently, reaches unintended recipients.

[83] Biology-inspired techniques as those developing from FET DELIS project / Subproject 5 (http://delis.upb.de/sub5.html), might be also useful in this regard.

Much of these suggestions correspond to thoroughly documented needs for long-term research and, to a certain extent, meet large acceptance. If there is a question to debate, it rather relates to the implementation conditions: level of committed resources, effective interdisciplinary character of such a research program, innovative tools (large scale simulations and virtual world environments) that should be created to support this research. Nonetheless, there is another aspect of the digital networks chapter that is not well recognized yet and needs to be explored in very innovative ways. The rapid rise of the *consumer networks* in the place of an *open information space* where individual consumers share opinions and experiences on a wide range of topics, including the evaluation of products and the appreciation of brands – and possibly use the acquired by this means information to construct preferences and make choices about products to purchase. Maybe the clearest example of such networks comes from the eBay's *online user feedback mechanisms* where buyers and sellers rate one another following transactions [97].

Box 11: Online Feedback Mechanisms (OFM)

C. Dellarocas [97]: "One of the most important new capabilities of the Internet relative to previous mass communication technologies is its bi-directionality. Through the Internet, not only can organizations reach audiences of unprecedented scale at a low cost, but also, for the first time in human history, individuals can make their personal thoughts, reactions, and opinions easily accessible to the global community of Internet users. Word-of- mouth, one of the most ancient mechanisms in the history of human society, is being given new significance by this unique property of the Internet. *Online feedback mechanisms,* also known as *reputation systems,* are using the Internet's bi-directional communication capabilities in order to artificially engineer large-scale word-of-mouth networks in which individuals share opinions and experiences on a wide range of topics, including companies, products, services, and even world events… The application of feedback mechanisms in online marketplaces is particularly interesting because many of these marketplaces would probably not have come into existence without them. It is, however, by no means the only possible application domain of such systems. Internet-based feedback mechanisms are appearing in a surprising variety of settings. For example, Epinions.com encourages Internet users to rate practically any kind of brick-and- mortar business, such as airlines, telephone companies, resorts, etc. Moviefone.com solicits and displays user feedback on new movies alongside professional reviews, and Citysearch.com does the same for restaurants, bars and performances… eBay's feedback mechanism is, arguably, the best-studied online feedback mechanism to date. One of the most remarkable aspects of eBay is that the transactions performed through it are not backed up by formal contractual guarantees. Instead, cooperation and trust are primarily based on the existence of a simple feedback mechanism. This mechanism allows eBay buyers and sellers to rate one another following transactions and makes the history of a trader's past ratings public to the entire community".

Beyond reputation enhancing mechanisms, online feedback networks usually appear as product review sites, online opinion forums, chats, discussion lists and, at a different level, develop over closed users' communities (such as instant messaging groups). Various studies suggest that online word-of-mouth might significantly affect consumer behavior, awareness in some cases, and preferences in others [98]. Maybe the link between word-of-mouth and product's market success would need further investigation to be accurately established [ibid.]. Yet, a more recent econometric study with data from the movie industry shows that online ratings posting during the first week of a new movie's release can form the basis for accurate forecasting of that movie's future box office revenues [99]. Moreover, many seem to believe, according to a US survey, that the use of online word of mouth is, to a certain extent, a substitute for both traditional advertising and for offline word of mouth [100] and it undoubtedly acts in a complementary way with traditional and online advertising.

Clearly, online feedback mechanisms intensify the interdependencies between customers, brands and their competitors, with two major implications. On the one side, they can serve as promotion channel for the firms, which would "strategically manipulate" the information flowed over these networks[84]. On the other side, these mechanisms should be considered as potential consumers tools in addressing *information asymmetries* [100, 102]. These opposing considerations suggest that there are many interesting issues that need to be addressed in order to realize the influence of these networks on product sales. They invite for research in the organization, functionality and modeling of the digital networks and the design of mechanisms against *opportunistic* behaviors.

Moreover, one might call for considering consumer feedback networks in a broader framework, that of a *set of socially derived knowledge resources,* available to the online consumers, to help them to manage the overload of information that is disseminated over the Internet. Where does it come from?

The online world that is now emerging on the top of the cyberinfrastructure is not *information asymmetric*[85] in the old sense. Search over the web is not exactly about searching for prices. The information disseminated by search engines is essentially determined by a complex system of algorithms that provides to the Internet users a blend of *search* and product location functionality *(find)* with advertising and interactive marketing. Morgan Stanley has labeled this typical of the Internet opportunity to deliver rich and essential information in only a few sessions as *Search/Find/Obtain model (SFO,* and recognizes to it the power of a global reality driven by the majors of the Internet, Yahoo!, Amazon, eBay, Microsoft – with strong SFO momentum becoming increasingly apparent for music & digital media and used items is [105, 106]. Frequently, these SFO sessions embed transaction capabilities *(obtain)* that allow a user to get the product/service

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[84] Anecdotal evidence suggests that firms sometimes use "strategically" the online feedback mechanisms to marketing purposes, by anonymously adding their own promotionally-biased messages to the total mix of posted opinions [101]. As reported by C. Dellarocas, *"in February 2004, due to a software error, Amazon.com's Canadian site mistakenly revealed the true identities of some of its book reviewers, it turned out that a sizable proportion of those reviews were written by the books' own publishers, authors, and competitors. The music industry is known to hire professional "posters" who surf various online chat rooms and fan sites in order to post positive opinions on behalf of new albums" [ibid.].*

[85] The term *information asymmetries* signifies the fact that sellers often possess more information than is available to consumers. This motivates them to act *opportunistically*, to promote their own strategic interests [103]. Joseph Stiglitz is one of the initiators of the *information asymmetries* concept which has considerably influenced the economic thought and it was for this contribution to the theory of information asymmetries that he shared the Nobel prize with George A. Akerlof and A. Michael Spence. In this regard, we also notice the highly relevant for the purposes of our analysis comment of S. Ioannides [104]: *"the introduction of the concept of asymmetric information marks a significant break with established micro-theory, as it implies an idea about information as independent of prices".*

she/he is interested in, but the important issue here is not how effective the Internet is to provide a transactional end to an interactive dialogue between a buyer and a customer.

In practice, the SFO model combines with Web's outstanding presentation efficiency and various online marketing and dialogue-initiating channels to bring to a potential consumer a rich *information-based experience* with a product/service she/he may be interested in, prior to touching it. And the content "posted" by the Internet users themselves *(the knowledge of the many)* adds another loop of information in the decision-making process. This *rich experience* is the real novelty the Internet makes happen.

Box 12: The *creative* behavior of a cyber-consumer

The Internet provides to the consumer a variety of ways to get *experience* with a product/service:

- Through online search and information gathering, online product appreciation and testing.
- By obtaining interactive and "personalized" advertising through web and mobile marketing.
- As a by-product of various online activities (participation in online forums and conversations, access to other users' feedback, *slashdot-ing* etc.).
- By selectively aggregating, with the use of smart Web-based applications, all these forms of *content* (including "user-generated content", for example blogs' content) in individual (or community's) *always on, personalized* or *communitized*, web pages.

In this context, the process of information perception and evaluation *(time-to-decide)* might "bias" the whole consumer decision-making process *(time-to-decide plus time-to-act)* and this is in a nutshell what *information economies* bring to the table. In brief, the information becomes a critical determinant of purchase behavior and this has several implications:

i) Theoretical: What is decision-making in such information-rich environments, where customer's decision process seems somehow to be decomposed in two interrelated sub-processes, an "information-biased" choice-making sub-process and an action-on-the decision one? How individual preferences are progressively constructed within the task of online information collection and evaluation (clearly a complex cognitive task)?

ii) Consumer welfare: Information in information-rich environments is still "imperfect" in the sense that customers acquire product information through search, that is a process peculiarly imbued with commercial and political values[86], and via navigation of the Web that is also "biased" by the topology of links[87]. Also, they learn about other users' opinions via online feedback networks that can be structurally

[86] See in particular A. Diaz [107].
[87] See *supra*.

"vulnerable" to strategic manipulation[88]. What technology assets and cognitive resources could make cyber-consumers *organizationally efficient* and *creative* in processing information in these conditions of "information excess"[89]?

iii) Competitive dynamics: The emerging information economies offer an "unprecedented visibility" into the performance of advertising and marketing campaigns and demonstrate the high value of intangible assets, such as brand and production promotion, customer relationship management and business process designed to incorporate user-producer interaction. How could firms act further to leverage opportunities related to the rise of the *creative consumer* and how should they manage the knowledge that is increasingly produced through a cyberinfrastructure-mediated interaction with their customers[90]?

Developing a unified explanation of consumer decision-making in these information-rich environments, an economic theory for the cyber-consumer and the technology environment that will support her/his organizational efficiency, are major research challenges. Once again, interdisciplinary approaches are strongly required. Special attention should be accorded to the development of methods and tools of *neuroeconomics*, a new field that already demonstrates a capacity to meld natural and social science concepts to the study of human behavior[91].

Recommendation: A central goal of EU communication policy, as implemented through many Grid projects[92], is to define and build a cyberinfrastructure that facilitates the development of new network organizational forms consistent to the requirements of Information Society. Science

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[88] See *supra.*

[89] The tasks of online information collection and evaluation in the context of information-rich environments resembles to a *knowledge creation* process. Economic theories, in particular New Institutional Economics, recognize to economic organizations (firms, networks etc.) the ability to create, transfer, assemble, integrate and exploit knowledge assets *(the firm as repository of knowledge)* which finally provides to them the foundations for competitive advantage [108, 109]. The same theories however are almost silent on customer's knowledge assets and customer's organizational efficiency in processing and managing knowledge…

[90] The issue of effectively managing private information, with the use of Privacy Enhancing Technologies (PET) technologies enhancing privacy, is also one of the important requirements for sustainable information economies that should be addressed in this context.

[91] In a recent paper published in *Cognition and Behavior,* P. Glimcher and A. Rustichini define neuroeconomics as the consilience of brain and decision: *"Economics, psychology, and neuroscience are converging today into a single, unified discipline with the ultimate aim of providing a single, general theory of human behavior. This is the emerging field of neuroeconomics in which consilience, the accordance of two or more inductions drawn from different groups of phenomena, seems to be operating. Economists and psychologists are providing rich conceptual tools for understanding and modeling behavior, while neurobiologists provide tools for the study of mechanism. The goal of this discipline is thus to understand the processes that connect sensation and action by revealing the neurobiological mechanisms by which decisions are made" [110].*

[92] See in particular http://www.cordis.lu/ist/rn/grids.htm

already benefit from cyberinfrastructure projects[93]. But research in business and consumer digital networks needs to be further supported and acquire a strong proactive interdisciplinary character. Moreover, research in the emerging area of information economies should embrace the key issues of: i) decision-making in an information-rich world (a complex issue that calls for interdisciplinary research between economics and behavioral sciences, psychology and neurobiology, to investigate the neural substrates of cognitive and emotional processes involved in product-choice related decisions) and, ii) theoretical tools and models for online consumer feedback networks, to study the consumer welfare increase-potential these networks promise[94]. Europe is clearly behind the US in the area of digital networks and information economies, as revealed by a recent "critical themes analysis" in the (narrower) area of electronic commerce [113]. The challenge for Europe is to use the instant advance that possesses in certain technologies of the cyberinfrastrucure, to design effective interdisciplinary research that can contribute to build new types of knowledge organizations (including cyberconsumer's organizational resources) with increasing efficiency.

4.4. The triangle Internet, Mobile, Wireless (or beyond "beyond-3G")

Research in this area is critical for sustaining, in the future, Europe's leading position in second and third generation of mobile communications technologies (2G/2.5G, 3G). European leadership in this industry is not irrelevant to the EU collaborative R&D that created the conditions for globally successful standards, and to the EU policies "pushing" for a pan-European GSM system[95]. But now, we are entering a new phase of growth in the mobile and wireless sector as mobile applications and services converge with the Internet and create requirements for increasing bandwidth and multimedia functionality. Growth factors for wired and wireless Internet appear therefore to be similar *(i.e. rich applications),* as the pervasive capacity of voice-over-IP applications demonstrates. Broadly speaking, the major R&D issue in the new era is what is "4G" or, better "B3G (beyond3G)", a term that signifies more than a hypothetical forth mobile generation: a future landscape consisting of network heterogeneity, permanent technology diversity, integration of different technologies (including seamless convergence between fixed and mobile infrastructures) and novel IP-based multimedia services,. It is about, in the terms of H. Kremling from Vodafone[96], a framework for *ambient service delivery* (based on ever higher volumes of multi-sensory data) that enables *optimal* ambient interactions *anywhere* and across heterogeneous networks[97]. These include (beyond wired networks): the personal level (personal/body area/ad hoc networks), the local/home

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[93] We notice in particular the EU funded project EGEE (http://egee-intranet.web.cern.ch/egee-intranet/gateway.html) and UK e-Science Program (http://www.rcuk.ac.uk/escience/).

[94] It is very important to encourage in this regard experimentation with concepts as *preference networks* [69] and apply biology-inspired techniques such as *virus networks* [111] and *tagging* [112].

[95] For an interesting consideration of 2G/3G mobile systems, see reference [114].

[96] See the presentation of H. Kremling at the ITS Mobile & Wireless Communications Summit 2005;
see: http://141.30.121.45/~summit/downloads/pp/panels/b3g/1_Kremling.pdf

[97] We report here on conclusions from the panel "B3G and 4G: What is it good for?" at ITS Mobile & Wireless Communications Summit 2005 (Dresden). Presentations of the participants in this panel are available at http://mobilesummit2005.org/session.php?session=103. They give a generic overview of the latest perceptions of what the functionality of B3G and 4G environments should be.

level (WLAN, Vevicular – VAN, Ultra Wideband – UWB), the cellular level (UMTS) and the wide area level (digital broadcast, new radio and satellite).

In mobile and wireless technologies (network technologies, applications, services), the EU invests a considerable amount of each Framework Program's budget (about 10% of 6FP's resources). Beyond EU level research investments, members-states run nationally funded R&D programs and equipment manufacturers and network equipments do invest considerable resources in R&D and actively co-ordinate their activities[98]. The European industry realizes that in order to face future challenges, research should go beyond products upgrade, to develop large-scale approaches to system research and development of innovative network technologies and novel applications and services. In point of fact, competition from outside Europe also invests considerably in R&D: as it recognized in a related report published by *eMobility* initiative[99], Asian countries, mostly Korea[100] and China, are making substantial efforts to overtake Europe; and the US invests its defense budget in supporting technological advances, in particular in the emerging area of short range wireless technologies. What *is long-term and effective R&D* in these investments in different platforms and technologies? In line with our definition of long-term research in terms of high impact / high risk but effectively selected priorities, we propose a research program that incorporates the newly established perspective of *commons*[101] in the management of spectrum. To explain how the *commons perspective* relates to most of the upcoming challenges in the sector and why it influences the direction for high risk / high impact research, we start our analysis from a recent ESTO-IPTS report on the potential of 4G [52].

This report identifies two scenarios for the development of the industry, a *linear 4G vision* and a *concurrent 4G vision*: *"The first scenario is an extrapolation from current trends towards increasing the bandwidth delivered by mobile communications and envisages the widespread availability of 4G mobile communications some time around 2010. This scenario projects forward the view of mobile communications as having evolved through a series of successive generations, a view that it is implicit in the term 'fourth generation'. (This scenario is referred to in the report as the 'linear 4G vision'). The alternative scenario (referred to in the report as the 'concurrent 4G vision') considers the possibly disruptive impact of the emergence of public wireless local area network (WLAN) access. To a limited extent WLAN access is already available today, and plans are*

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[98] The more recent example of such an industry-wide R&D program is "eMobility: The Mobile and Wireless Communications Technology Platform" (http://www.emobility.eu.org/). We notice also the existence of two very active industry-wide groups expressing mainly views of equipment manufacturers, WWRF – Wireless World Research Forum (http://www.wireless-world-initiative.org/) and WSI – Wireless Strategic Initiative (http://www.wireless-world-initiative.org/), as well as the Eurescom – European Institute for Research and Strategic Studies in Telecommunications (http://www.eurescom.de/) which is mainly backed by the European Telecoms.
[99] See: http://www.emobility.eu.org/about_us.html#theMobile
[100] For a comprehensive overview of Korean strategy in communications sector, see the presentation of E. Bolin (IST Strategies in Korea) at FISTERA Conference "IST at the Service of a Changing Europe by 2020: Learning from World Views", June 2005, Seville (available at http://fistera.jrc.es/docs/Final%20conference/presentations/session%205/Bohlin%20Korea%20Case%20report.pdf).
[101] See footnote 16.

afoot to deploy large numbers of so-called "hot-spots" offering semi-mobile Internet access. This approach enables a high bandwidth service to be offered at relatively low cost in specific locations where usage is likely to be concentrated [ibid.]. Although many things have been changed from the publication of this report (Feb. 2004), and both visions have been evolved, a certain dichotomy, not very different from what ESTO report describes, seem to persist.

It might be now a *post-linear 4G vision* that impinges on the current European research approach, as it is implemented through 6FP's projects and as it comes out from initial FP7 designs about *ambient service delivery*[102]. It is very much broader than it was the 4G linear-vision, at the time ESTO report has been written, since it incorporates the very realistic assumption of a permanent heterogeneity of networks and applications that should be seamlessly integrated. Essentially, it emphasizes the need for research in systems that, simultaneously, provide *increasing and efficiently used bandwidth* and create *user content-defined* innovative services (this is a real evolution, non-linear, from the times we were discussing transition paths to 3G). Within the new vision, access to these networks, applications and services, with the use of Wireless Access Systems technologies such as WLANs, is actively promoted in the sense that the issue is considered as belonging to consumer welfare policies. As a matter of fact, the Commission has recently decided to make available a substantial amount of radio spectrum through the EU for WLANs (Wi-Fi), with the objective to *"provide access on the move to the Internet and private networks"* in a 'nomadic' environment, *"meaning the user can take his laptop to access these services at any location within the range of a hotspot"*. Very appropriately, the post-linear 4G vision looks also at the necessary policy measures that should complement, and facilitate, the research agenda. In this context, a new approach of spectrum policy in EU is under preparation focusing on new mechanisms (emphasizing on markets for spectrum trading) that can improve spectrum management and, consequently, support innovation and competitiveness[103].

Box 13: Commission Decision of 11.06.2005 on the Harmonized use of radio spectrum in the 5 GHz frequency band for the implementation of Wireless Access Systems including Radio Local Area Networks (WAS/RLANs) / MEMO/05/256

What are these technologies used for?

Today, radio local area networks (RLANs, also known as Wi-Fi) can be used in so-called "hotspots" that can be found at airports, hotels, coffee shops, etc. They allow users to connect their laptop to the Internet and to make phone calls using "Voice over IP" (see MEMO/05/46). There is increasing evidence that RLAN networks can provide effective Internet services, especially as a complement to cellular and residential broadband services, or across municipal or Wireless Internet Service Provider (WISP) networks. RLANs are part of a wider category called Wireless Access Systems that give their users access to broadband communications in a "nomadic" environment, meaning the user can take his laptop to access these services at any location within the range of a "hotspot".

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[102] See footnote 8; see also the presentation of A. de Albuquerque (European Commission, INFSOUnitD1) at ITS Mobile & Wireless Communications Summit 2005 (Dresden) – available at http://141.30.121.45/~summit/downloads/pp/panels/b3g/5_deAlbuquerque.pdf.

[103] See in particular the work of the Radio Spectrum Policy Group (RSPG), established under the Commission Decision 2002/622/EC (http://rspg.groups.eu.int/about/index_en.htm).

Why a Commission Decision on this subject?

Taking into account the potential congestion in the existing 2.4 GHz frequency band, it is important for industry to be given the legal certainty that a substantial amount of spectrum will be made available for WAS/RLANs throughout the European Union in a harmonized way. The new Commission Decision will ensure that sufficient spectrum is soon made available in all Member States in the 5 GHz range (5150-5350 MHz and 5470-5725 MHz) to accommodate new equipment, thus giving impetus to new innovative services and access to broadband. As well as encouraging the uptake of innovative services, the main objective of this action is to ensure the creation of a single market for devices using Wi-Fi, such as laptops. The RLAN systems using the new bands will be faster than existing Wi-Fi (typically 54 Mbit/s instead of 11 Mbit/s). Rather than being a band open to any application, like 2.4 GHz, the 5 GHz frequency bands are to be shared by RLAN with a limited number of other radio spectrum users, namely military and satellite services. This gives RLAN a better operating environment, but requires some coordinated technical coexistence criteria, which were agreed at the World Radiocommunications Conference of the International Telecommunication Union (ITU) in 2003 (WRC-03)… The Commission Decision gives a legal basis for the level of protection that all the different services operating in the 5 GHz range can expect within the EU.

How can this Decision facilitate innovation and the rapid spread of broadband services?

Today's Commission Decision also gives a large amount of flexibility with respect to what type of service or network topology the technology is used for. Manufacturers are already working on new innovative applications, such as the spreading of self-building networks. So-called "mesh networks" are new ways of connecting users to broadband and extending the range, in some cases without additional network costs. In metropolitan areas, in particular, these networks may trigger substantial changes compared to today's communications landscape. As other spectrum users must be protected, there are, however, limits to the range that one can achieve with WAS/RLAN equipment that uses the 5 GHz frequency bands. Consequently, this will limit to some extent the prospects of bringing broadband into rural areas where longer distances need to be bridged for access. This is where a technology like WiMAX could come into play. WIMAX is a technology that has substantially more range (typically in the order of several kilometres), but also uses a higher power than Wi-Fi (in other frequency bands)…. It should be noted that when WIMAX equipment is used in the bands identified by this Commission Decision the relevant power limits for WAS/RLAN must be respected.

Given the fast steps forward of the "4G linear-vision", does it still exist a post-concurrent 4G vision as well? It does! It ambitions to provide a radical solution to the organization of wireless infrastructures that, in effect, work very differently than the Internet though the wires. The driver for such a disruptive trajectory is the idea of unlicensed spectrum that, thanks to advances in technology, can be efficiently managed in a very distributed way through a *sharing model,* called in the jargon of the academic and business community "wireless commons", that can establish a new generation of cooperation and aggregation mechanisms enabling a truly decentralized wireless grid. In fact, advocates of commons [16, 115, 116, 117, 118] claim that collections of *smart* wireless devices (e.g. smart radio equipment *"owned by individuals, much like automobiles and PCs")* can share spectrum capacity efficiently, without defining exclusive rights on it, and even cooperate in the creation of new capacity. They do expect from new *transceivers* to dynamically change their frequency, modulation, power levels and to have the capacity of relaying traffic (or "lending" their antenna to neighboring nodes), thus generating *excess* wireless network capacity. The owners of such an excess capacity, exactly as it happens with distributed computers (SET@home and Grids) and automobile space in California (car-pooling), "*can share in order to produce wireless communications systems" [16]*. To give more credibility to their arguments, *spectrum opennists* refer to novel theories of *shareable goods* and the emergence of sharing as a third way of economic production, beyond *markets* and *hierarchies,* and they state Wi-Fi's spread as the success case for unlicensed spectrum policies [ibid.]. They therefore ask for allocating more spectrum for dedicated unlicensed use and turn against recommendations for policy reforms that exclusively focus on private spectrum licensing.

Box 14: Towards Wireless Commons

Y. Benkler [16]: "The declining cost of computation and the increasing sophistication of communications protocols among end- user devices in a network made possible new, sharing-based solutions to the problem of how to allow users to communicate without wires. Now, instead of having a regulation-determined exclusive right to transmit, which may or may not itself be subject to market re-allocation, it is possible to have a market in small scale capital goods which embed in the devices the technical ability to share capacity and cooperate in the creation of capacity… The reasons that the owners share are relatively straightforward in this case. Users want to have wireless connectivity all the time, to be reachable and immediately available everywhere. But they do not actually want to communicate every few microseconds. They will therefore be willing to purchase and keep turned on equipment that provides them with such connectivity. Manufacturers, in turn, will develop and adhere to standards that will improve capacity and connectivity. Given that "cooperation gain" is the most promising source of better-than-linear capacity scaling for distributed wireless systems, these standards should gravitate towards interoperability and mutual awareness of requirements… Users, then, have incentives to keep systems turned on, manufacturers have incentives to "share nicely," and defections from sharing are likely to be reasonably identifiable. What remains for consideration in the regulatory process is how much, if any, background regulation of systems is necessary to constrain specifically strategic defections from cooperative standards, and in what flavors – as pre-certification rules, as liability rules, etc. This is a hard problem that will not likely be solved theoretically, but rather through practical experimentation with different regimes in different parts of the already-regulated spectrum…

We are beginning to see in this space the most prominent example of a system that was entirely oriented towards improving the institutional conditions of market-based production of wireless transport capacity as functionality flows – connectivity minutes – shifting to enable the emergence of a market in shareable goods – smart radios – designed to provision transport on a sharing model".

In the public debate, commons advocates (or spectrum opennists) do not oppose to linear 4G-visionists. The divide in public debate, as it has appeared in the US in the last years, where this discussion entertains a very creative conflict of ideas, is between commons advocates and property-rights advocates and the issue is about efficient spectrum management. Property-rights advocates, with reference to old G. Hardin's paper [119] argue that anytime a resource is provided for free, it is over-used and congested and, as a result, a "tragedy of commons" usually arises. In addition, they criticize spectrum opennists for ignoring the problem of dispute resolution in a commons system and suspect the commons approach to finally introduce new costs of regulation [120, 121, 122]. Whatever the issue of this debate would be, clearly there is a tendency for opposing sides to move closer [123], they are already two major implications:

i) Liberalization and flexibility in the use of spectrum, which requires de facto or de jour private property rights (through establishing markets and trading mechanisms[104]), are increasingly acknowledged as more efficient principles for spectrum management than the "old" administrative planning process ("command and control")[105].

ii) Policy makers in the US[106], EU[107] and everywhere in the world[108] are considering to move simultaneously in a *pro-market* and *pro-commons* direction, by designing a common-mix of regulatory approaches and searching for the appropriate balance between fractions of flexibly-licensed and (unlicensed) commons-managed spectrum [109,110].

The shift to more efficient spectrum management techniques, of course, will lower opportunity costs and encourage changing the use of many spectrum fractions to offer new services and stimulate innovative uses of new technologies (as for instance low-power devices and low power transmissions in bands allocated to mobile or television networks[111]). An interesting question arises however when we take in consideration also the technology dynamics of the different allocation modes. From a strict technology perspective, licensed systems managed through spectrum usage rights provide just a good level of technology neutrality. While commons, because they are challenging the strong assumption of *interference*[112], they have opened the door to a fundamental revisiting of wireless technologies and architectures. In fact, commons advocates, with reference to

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[104] Implemented as secondary markets that reassign wireless bandwidth next to a regulatory allocation (this would give a mobile operator, for instance, the opportunity to sell the frequency space allocated to its license for 3G services to a Wi-Fi operator looking to expand capacity for Voice-over-IP services)…

[105] The traditional model for managing spectrum (command-and-control) has been based on a licensing regime where governments grant licensees restrictive power (including technical requirements to be respected and type of service to be delivered) on pre-defined frequency blocks of spectrum.

[106] See: FCC 2002 Spectrum Policy Task Force Report, ET Docket no 02-135 (available at http://www.fcc.gov/sptf/).

[107] See: Ph. Lefebvre's (EC) presentation at the Workshop "An Open Future for Wireless Communications", Cambridge (UK), April 2004 (available at http://www.thecii.org/events/wireless-2005-04-19/1-lefebvre.pdf). For a more secondary markets-oriented view, see: G. Louth's (Ofcom) presentation at the same workshop (available at http://www.thecii.org/events/wireless-2005-04-19/2-louth.pdf).

[108] See reference [124].

[109] With a smaller and rather diminishing part of the spectrum being traditionally regulated (under "command and control" process).

[110] In the UK, current distribution of spectrum across these models has as follows: "command and control": 94%, unlicensed: 6%, market forces zone: 0%.

[111] Unlicensed low power systems may share frequencies with other flexibly-licensed systems without causing interference to them.

[112] Interference means the unwanted noise from nearby radio sources that affects the quality of a wireless communication. Interference's avoidance has justified early decisions for spectrum separation in blocks of frequencies and for legally enforced exclusivity in tiny or wider fractions of spectrum (command and control).

modern wireless systems, believe that unlicensed spectrum systems can be very efficient at minimizing interference. And novel technologies may allow for effective wireless communications without the obligation to a priory assign dedicated frequency bands to different channels [116].

Four innovative techniques are of particular interest towards *optimizing interference* and *transforming frequency-based use of spectrum* [116, 123, 125, 126, 127, 128]: i) (overlay) cognitive radio sensing and adapting to their RF environment (cognitive radios could sense if a specific frequency band is currently in use, emit in that band if not, and quickly switch to another band if a new device begins to emit in that band[113]); ii) (overlay) Smart Antenna Technologies that improve over-reception-performance (by distinguishing, with the aid of several observations, the signal from the noise and lock-on to the first); iii) (underlay) UWB – Ultra-Wideband trading-off bandwidth for power (UWB transmissions broadcast very short pulses over a very large bandwidth thus reducing a radio source's power levels below the "noise floor" of other devices); v) (architecture) mesh networks that use very little power thus minimizing interference problems (a mesh network can effectively communicate with a nearby computer, and another one, and so on, and in that way a larger scale relay network to form by turning receivers into transmitters, therefore adding capacity to the network "as it is consumed"[114]). All of these techniques have several weaknesses to improve if they have to be employed in a full commercial environment, but various communities of engineers, start-ups and research projects push fast cycles of experimentation with them, motivated by the ongoing enlargement of the "under commons" fraction of the spectrum[115].

How far back can the collaborative wireless frontier be pushed? A fairly good appreciation of the situation is suggested by W. Lehr. In all likelihood, there will be a mix of technologies and business models evolving together with a common-mix of regulatory approaches: *"The convergence of computing and communications, which is pushed still further by the growth of wireless, makes it more difficult to define where the network "edge" is and what functionality should be included in equipment versus networks. At this stage, it is far from clear which technologies will work best with which business and regulatory models to serve which user needs" [118].* What is more certain is

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[113] Technologies under development can go further in exploiting "free of current use" frequencies (holes), a process called "opportunistic sharing or interweaving", to the point that they can opportunistically redistribute the allocated spectrum, without needing to know what is exactly the prior allocation scheme. In this regard, DARPA has invested the XG research program with the objective to develop particularly opportunistic sharing mechanism able to adapt in "hostile" environments (see: http://www.darpa.mil/ato/programs/xg/).

[114] Mesh networks can be used to deliver both data and voice services and with a mix of underlying technologies, from cellular to software radio and UWB. Mesh networks are considered to be innovative in terms of their ability to increase capacity as the geographic density of (low-powered) nodes increases.
Note: A conceptually interesting approach to the engineering of mesh wireless systems with high levels of interconnectivity / growth and low power requirements, comes from MIT Media Lab under the name of "viral communications" (see: http://www.darpa.mil/ato/programs/xg/).

[115] This is not to say that a licensing/property regimes is not capable to integrate these technologies. They can do even give some incentives to the development of some of them but, generally speaking, they are rather friendlier to other innovations (it might be more stimulating for technologies like auction-based bandwidth trading or secondary markets creating and monitoring technologies).

that the ways through which spectrum is made available will influence network architecture and vice-versa, wireless network architectures are expected to influence the ways spectrum will be used[116].

To sum up: "Conventional" approaches, as the *post-linear 4G model,* attempt to understand wireless networks as an extension of the Internet architecture, with "core" and "end" parts, where growth is driven by *rich applications* (that should be yet "discovered") enjoying high bandwidth and flexibly-allocated spectrum. A commons approach, which substitutes open and self-regulated entry for exclusive control, explore different network principles so that wireless capacity can be built in a cooperative manner (yielding *cooperative gains)* where *"the whole is greater than the parts"* [117]. By doing so, commons tend to foster decentralized networks with very edge-driven intelligence, located in users' premises that will be provided as commodity equipment by equipment suppliers'[118]. How these networks will be operated to provide consistent service and macro-coordination (by

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[116] We remind R. Nelson's comment that technologies and institutions are evolving together [45].

[117] It is worthwhile to notice that DARPA in US intends to foster research along this technological trajectory (starting wireless engineering almost from the scratch). In July 2005, DARPA has announced a "Control-Based Mobile Ad-Hoc Networking (CBMANET)" program that will design, develop, and demonstrate a Mobile Ad-hoc NETwork (MANET) *"based on a tabula rasa rethinking of wireless network architecture inclusive of distributed adaptive control mechanisms, cross-layer protocols tailored for wireless tactical environments, and reformulated network layering abstractions as warranted... The result will be a novel and advantageous MANET that dramatically improves performance from the end user's perspective for at least the following three reasons.*
First, a control-based network will more effectively allocate wireless network resources to meet user goals and operator constraints. Ideally these goals and constraints will be explicitly characterized in the form of a dynamically tunable objective function that reflects the network designer/planner's purpose and guides distributed cross-layer network adaptation. Examples of relevant goals and operational constraints include aggregate application utility maximization, resource availability, fairness, connectivity, quality of service assurance, mission-adaptive multi-level precedence and priority, and the desired network operating regime concerning probability of jamming, intercept, or detection.
Second, novel protocols suitable for wireless networking will be employed independent of historical constraints motivated by today's dominant networking paradigms. In particular, the CBMANET protocols will exploit cross-layer interactions in order to more effectively support tactically relevant network applications. Typical traffic loads are characterized by prioritized content, deadline-sensitive messaging, and a heavy emphasis on multicast.
Third, conventional network layering principles will be reconsidered to more effectively enable cross-layer interactions and to better modularize user concerns such as latency, capacity, energy, fairness, and priority. The remodularized stack will provide interfaces and hooks tailored to support the distributed adaptive control mechanism in the spirit of design for manageability". (document available at http://www2.eps.gov/spg/ODA/DARPA/CMO/Reference%2DNumber%2DSN05%2D34/Synopsis.html).

[118] In this regard, see in particular the presentation of W. Lehr at the Workshop "An Open Future for Wireless Communications", Cambridge (UK), April 2004, available at http://cfp.mit.edu/events/slides/jun05/William-Lehr_jun05.pdf

design) is yet unclear but the history teaches us that any new network architecture brings in a new type of firm providers network service (Internet – ISPs etc.)…

Recommendation: In the very next years, mobile devices will have access speeds comparable to PCs and "built-in" capacity to connect to both G and Wi-Fi networks. Seamless interaction of the mobile infrastructures with wired broadband Internet is a realistic perspective. Europe designs carefully its research plan in these matters by incorporating a more user-focused perspective than in the past[119]. The investments that are necessary to implement "beyond 3G" environments, and the costs which are requested for the consumer to pay to have access into these services, may however slow down the adoption curve of "beyond 3G" networks and services (as it happens now with 3G networks and services) and raise reasonable anxiety about the future of European leadership in the mobile industry. It is very likely that a reform in the spectrum regulation and management, currently in process, will contribute to lower entry barriers and possibly give to the mobile industry more market efficiency and flexibility (and the opportunity to reap the rewards of previous investments in 3G licenses). At the same time, new "radical" approaches appear to efficiently manage spectrum that focus on technology-enabled flexible and non-exclusive use of spectrum (i.e. unlicensed spectrum) and want to establish *commons* rules for allocation of wireless resources. They promise drastic advancements in new technologies as cognitive radio and UWB, where the EU has already invested effort and research budgets, and novel architectural considerations (mesh networks) of the mobile and wireless Internet that possibly make it architecturally different from the fixed Internet. Uncertainty is once again the perspective for technology development and business plans. The best response to uncertainty is diversity.

This report constitutes an attempt to broaden our concept of what uncertainty is "beyond 3G" in a way that will enable us to recognize the need for a coherent plan of systematic experimentation with wireless commons' technologies, regulation and socio-economic drivers. A limited in time but sufficiently funded program, with frequent evaluation steps, in the context of a "keep all options open" European strategy (beyond "beyond 3G"). Strengthening the existing and experimenting with the new, and ingeniously balancing efforts between the two, is the natural way to behave for a leader. Furthermore, research in the key area of mobile and wireless Internet needs to foster solid European architectural views, novel network layering abstractions, and models for understanding the wireless networks of tomorrow and exploring possible transition paths. Ultimately, architectural thinking over current and next generation mobile and wireless networks and services is a qualitative step forward that needs to be organized differently from currently employed "projects clustering" approaches.

5. Cross-cutting issues

The previous subsections have outlined opportunities for long-term research in the area of communications technologies and networks, organized in six key research areas. Four of them have

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[119] It is very interesting innovation in this regard the attribution to IPTS of a study about future mobile services and markets seen from a socio-economic perspective. For more details see reference [129].

been considered as highly related to the complexity management for the Internet and the Web. They bring in new challenges for basic research in *architecture design* and *network theories* and require real *interdisciplinary approaches.* The tools and most appropriate insights for understanding the issues raised in these contexts[120], come from four particular methodological flavors:

- Complex Systems
- Cognitive Systems
- Algorithms augmented with concepts and models from Mathematical Economics / Game Theory
- Computational Science.

[120] To give some examples: design next Internet architecture, explain the "robust, yet fragile" structure of the Internet, efficiently managing digital networks, effectively *sharing* the wireless resources, etc.

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