# Fundamental Limitations of current Internet and the path to Future Internet[1]

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## 1. INTRODUCTION

The Internet has become the most important medium for information exchange and the core communication environment for business relations as well as for social interactions. Millions of people all over the world use the Internet for finding, accessing and exchanging information, enjoying multimedia communications, taking advantage of advanced software services, buying and selling, keeping in touch with family and friends, to name a few. The success of the Internet has created even higher hopes and expectations for new applications and services, which the current Internet may not be able to support to a sufficient level. It is expected that the number of nodes (computers, terminals mobile devices, sensors, etc.) of the Internet will soon grow to more than 100 billion [1]. The services and open application interfaces will expand in a similar way and many of these services will be addressing essential societal needs in the domains of healthcare, transportation/automotive, emergency services, etc. Reliability, availability, and interoperability required by these services impose in turn to increase robustness, survivability, and collaborative properties of the Internet architecture. In parallel, the advances in video capturing and content/media generation have led to larger amounts of multimedia content and applications offering immersive experiences, e.g., 3D videos, interactive immersive environments, network gaming, virtual worlds, etc. compared to quantity and type of data currently exchanged over the Internet. Based on [2], out of the 42 Exabytes ($10^{18}$) per month of consumer Internet traffic, likely to be generated every month in 2014, 56% will be due to Internet video, while the average monthly consumer Internet traffic will be equivalent to 32 million people streaming Avatar in 3D, continuously, for the entire month.

All these applications create new demands, which to a certain extent can be addressed through "over-dimensioning" combined with the increase of Internet capabilities over time[3]. While the latter can be a satisfactory (even if sometimes temporary) solution to some cases, analyses have shown [4] that increasing the bandwidth to peta-bps on the backbone network will not suffice due to new qualitative requirements in, for example, highly critical services such as e-health applications, clouds of services and clouds of sensors, new social network applications

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[1] The views expressed are those of the authors and not necessarily those of the European Commission or any of its officials.

[2] The document addresses the majority of the FIArch Group experts' views but do not necessarily coincide with each member's personal opinion. This may be considered as an interim version, still to be updated/commented. Any contribution to the FIArchitecture Group is welcome at the following email addresses: fiarch@future-internet.eu or infso-future-internet@ec.europa.eu

like collaborative 3D immersive environments, new commercial and transactional applications, new location-based services and so on.

In brief, the question is to determine if the architecture (and its properties) itself might become the limiting factor of Internet growth and deployment of new applications. For instance, as stated in [5] "*the end-to-end arguments are insufficiently compelling to outweigh other criteria for certain functions such as routing and congestion control*". On the other hand, the evolution of the Internet architecture is driven by incremental and reactive additions [6]. Moreover, studies on the impact of research results have shown that better performance or functionality define necessary but not sufficient conditions for change in the Internet architecture (and/or its components); hence, the need also to demonstrate limits of the current architecture [7]. Thus, scientists and researchers from companies and research institutes world-wide are working towards understanding these architectural limits so as to progressively determine the principles that will drive the Future Internet architecture, which will adequately meet the abovementioned challenges.

***The Future Internet (FI) is expected to be a holistic communication and information exchange ecosystem, which will interface, interconnect, integrate and expand today's Internet, public and private intranets and networks of any type and scale, in order to provide efficiently, transparently, interoperably, flexibly, timely and securely services (including essential and critical services) to humans and systems, while still allowing for tussles among the various stakeholders without restricting considerably their choices.***

This novel, complex distributed environment may be considered from various interrelated perspectives: the networks and infrastructure perspective, the services perspective and the media and information perspective.
Significant efforts world-wide have already been devoted to define, build and validate the FI and/or some of its pillars. As major representative programs/frameworks towards FI we may highlight the Future Internet Assembly (FIA) [8] in Europe, the NetSE [9] in USA, the AKARI [10] in Japan and the Future Internet [11] program in Korea.

### 1.1 Scope and Purpose

The purpose of this current document is to identify, and to reach some understanding of, the different types of fundamental limitations of the current Internet and its architecture. The next step is to derive design objectives for the Future Internet and to identify those challenges that could possibly be met using current architecture and those that appear to demand a new or extended architectural foundation.

This report targets not only the Research and Academic community, but also the European ICT industry and decision makers (including but not limited to telecom operators, ISPs, networking equipment manufacturers and providers of value-added networking services).

The document outlines potential orientation to address them anticipating growth and functional evolution of the Internet. The rest of the document is structured as follows: Section 2 contains the necessary definitions used in this group so as to avoid misunderstandings due to the different background of the group's members. Section 3 explains the analysis approach used for identifying the main functionalities of the Internet and their associated limitations. These are described in Sections 4-8. Finally, conclusions are drawn in Section 9.

## 2. DEFINITIONS

Before describing the approach that the FIArch Group has followed, it is important to explain some definitions that we have used in our work.

We define as ***"architecture"*** a set of functions, states, and objects/information together with their behavior, structure, composition, relationships and spatio-temporal distribution[34]. The specification of the associated functional, object/informational and state models leads to an architectural model comprising a set of components (i.e. procedures, data structures, state machines) and the characterization of their interactions (i.e. messages, calls, events, etc.).

We define as ***"fundamental limitation"*** (of the Internet architecture) a functional, structural, or performance restriction or constraint that cannot be resolved with current or clearly foreseen paradigms as far as our understanding/knowledge goes. On the other hand, we define as ***"challenging limitation"*** a functional, structural, or performance restriction or constraint that could be resolved (as far as our understanding/knowledge goes) by replacing and/or adding/removing a component of the architecture that would in turn change the global properties of the Internet architecture. We also define the term ***"Re-engineering***" as a method for overcoming a challenging limitation, by the replacement of an instance of an existing component of an architecture that would not change the global properties of the Internet architecture.
In the following, we use the term:

- "***data"*** to refer to any organized group of bits a.k.a. data packets, data traffic, information, content (audio, video, multimedia), etc.
- "***service***" to refer to any action or set of actions performed by a provider (person or system) in fulfillment of a request, which occurs through the Internet (i.e. by exploiting data communication, as defined below) with the ultimate aim of creating and/or providing *added value* or benefits to the requester(s). Note that this document refrains from taking position on the localization and distribution of these APIs.
- ***"flexibility"*** to refer to the capacity of a system to adapt/react in a timely and cost-effective manner when internal or external events occur that affect its value delivery[5]. Flexibility can also be seen as the ability of a system to respond to uncertainty in a manner to sustain or increase the system's value delivery over time: it is under the assumption of existence of uncertainty and variability that flexibility becomes valuable.
- ***"dependability"*** as a collective term to describe the performance, the availability and its influencing factors: reliability performance, maintainability performance and maintenance support performance [6]. It also includes concepts as safety, integrity,

[3] Many definitions of (system) architecture have been formulated over time. We borrow the terms of our definition from Dewayne E. Perry and Alexander L. Wolf. "Foundations for the Study of Software Architecture". ACM SIGSOFT Software Engineering Notes, 17:4, October 1992, Garlan and Perry, guest editorial to the IEEE Transactions on Software Engineering, April 1995, and Booch, Presentation at Software Developers Conference 1999

[4] The time dimension is often omitted we include it here to keep a generic nature of our definition.

[5] The process of providing value to the users in terms of data, information, contents, services, benefits, quality, etc. This concept includes both functional (i.e. information, contents, etc.) and non-functional (i.e. quality) attributes; it also includes both objective (e.g. data) and subjective (according to users' perception of it, e.g. quality) value**.**

conformance, privacy, security, etc. and the concepts of systems' vulnerabilities and failures, along with the way we can minimize their frequency and impact;

## 3. ANALYSIS APPROACH

Since its creation, the Internet is driven by a small set of fundamental design principles rather than a formal architecture that is created on a whiteboard by a standardization or research group. Moreover, the necessity for backwards compatibility and the trade-off between Internet redesign and proposing extensions, enhancements and re-engineering of today's Internet protocols are heavily debated. Within the EC driven Initiative on Future Internet Architecture (FIArch), we have tried to identify and analyse the presumed problems and limitations of the Internet starting from the basic networking layers upwards before defining measurable requirements and objectives.

The emergence of new needs at both functional and performance levels, the cost and complexity of Internet growth, the existing and foreseen functional and performance limitations of the Internet's architectural principles and design model put the following base functionalities under pressure:

i) ***Processing/handling of "data"***: refers to forwarders (e.g. routers, switches, etc.), computers (e.g., terminals, servers, etc.), CPUs, etc. and handlers (software programs/ routines) that generate and treat/access/query data.

ii) ***Storage of "data"***: refers to memory, buffers, caches, disks, etc. and associated logical data structures.

iii) ***Transmission of "data"***: refers to physical and logical transferring and exchange of data.

iv) ***Control of processing, storage, transmission of systems and functions***: refers to the action of observation (input), analysis, and decision (output) whose execution affects the running conditions of these systems and functions.[6] This also includes any management functionality (e.g. systems, networks, services, etc).

In our approach, we have tried to characterize what the current Internet architecture fundamental limitations are and conclude with a basic consideration on the path to Future Internet. Three alternative paths have been considered during the discussions of the group to see if these limitations would lead to:

- Reengineer today's Internet protocols
- Redesign today's Internet Architecture in an evolutionary approach
- Design a completely new Internet Reference model

The conclusion of those discussions on the alternative paths is included into the 'conclusions' section of this document.

## 4. PROCESSING AND HANDLING LIMITATIONS

The fundamental restrictions that have been identified in the base function "processing/handling of data" are:

[6] Note that by using these base functions, the **data communication** function can be defined as the combination of processing, storage, transmission and control functions applied to "data".

- *The Internet does not allow hosts to diagnose potential problems and the network offers little feedback for hosts to perform root cause discovery and analysis* [12]. In today's Internet, when a failure occurs it is often impossible for hosts to describe the failure (what happened ?) and determine the cause of the failure (why it happened ?), and which actions to take to actually correct it.

- *The misbehaviour that may be driven by pure malice or selfish interests is detrimental to the cooperation between Internet users and providers.* Non-intrusive and non-discriminatory means to detect misbehaviour and mitigate their effects while keeping open and broad accessibility to the Internet is a crucial limitation to overcome [13], [TRILOGY].

- *Lack of data and service identity* is damaging the utility of the communication system. As a result, data and links to service handlers, as ‘economic objects’, traverses the communication infrastructure multiple times, limiting its scaling, while lack of content ‘property rights’ (not only author but also usage rights) leads to the absence of a fair charging model [SMOOTH-IT].

- *Lack of methods for dependable, trustworthy processing and handling* of *network and systems* infrastructure and essential services in many critical environments, such as healthcare, transportation, compliance with legal regulations, etc.

- *Real-time processing.* Though this is not directly related to the Internet Architecture, the limited real-time processing capability poses additional limitations. On the other hand, many application areas (e.g. sensor networks) require real-time Internet processing at the edges nodes of the network.

## 5. STORAGE LIMITATIONS

The fundamental restrictions that have been identified in the base function “storage of data” are:

- *Lack of context/content aware storage management:* Despite the significant dropping price and increasing size of the storage, the amounts of data that are created today require ever-growing amounts of storage. However, data are not inherently associated with knowledge of their context. This information may be available at the communication end-points (applications) but not when data are in transit. So, it is not feasible to make efficient storage decisions that guarantee fast storage management, fast data mining and retrieval, refreshing and removal optimized for different types of data [14].

- *Lack of inherited user and data privacy*: The lack of context/content aware storage management is also closely related with the lack user and data privacy. In case we include data protection/encryption methods (even using asymmetric encryption and public key methods), data can’t be efficiently stored/handled. On the other hand, lack of encryption, violates the user and data privacy. More investigations into the larger privacy and data-protection eco-system are required to overcome current limits of how current information systems deal with privacy and protection of information of users, and develop ways to better respect the needs and expectations. [30], [31], [32]

- *Lack of data integrity, reliability, provenance, and trust,* targeting the security and protection of data; this covers both unintended disclosure and damage to integrity from defects or failures, and vulnerabilities to malicious attack.

- *Lack of efficient caching & mirroring:* There is no inherited method for on-path caching and mirroring of data/content (compared to off-path caching) that could deal with issues like flash crowding, as the onset of the phenomenon will still cause thousands of cache servers to request the same documents from the original site of publication. Indeed, packet processing at network layer does not enable processing of the information carried in these packets. Inspecting packet along the path on the other hand breaks fundamental objectives of the Internet architecture including scalability, robustness, and security [OCEAN],[COAST].

- *Lack of data integration and federated storage solutions*: There is an increasing need for access to federated distributed storage resources, particularly in view of collaborative activities and ad-hoc service compositions or sensor data aggregation. This limitation may be extended to cover also access to service handlers. In this respect, it is important for distributed and interoperable solutions to be capable of handling different types of storage models for the widest range of purposes.

## 6. TRANSMISSION LIMITATIONS

The fundamental restrictions that have been identified in the base function "transmission of data" are:

- *Lack of efficient transmission of content-oriented traffic:* Multimedia content-oriented traffic comprises much larger amounts of data as compared to any other information flow, while its inefficient handling results in retransmission of the same data multiple times and possibly from sub-optimal sources/paths. CDN and more generally solutions using distributed caching reduce the problem under certain conditions, but can't extend to meet the Internet scale [15]. Transmission from centralized locations creates unnecessary overheads and non-optimal transmission when massive amounts of data are consumed [ALICANTE][ COAST][COMET].

- *Lack of integration of devices with limited resources to the Internet as autonomous addressable entities.* Environments such as sensor networks (or even nano-networks/ smart dust) and machine-to-machine (M2M) environments operate with such limited processing, storage and transmission capacity that partially operate the necessary protocols in order to be integrated at the Internet as *autonomous addressable entities.* This raises the question of applicability of the hour-glass model for such devices. For example, Internet demands at least the RTP protocol over the TCP/IP protocol stack to perform data streaming [IoT-A].

- *Security requirements of the transmission links:* Communications privacy is not only protecting/encrypting the exchanged data but even not disclosing that communication took place. It is not sufficient to just protect/encrypt the data (including encryption of protocols/information/content, tamper-proof applications etc), *but also protect the communicati*on itself, including the relation/interaction between (business or private) parties.

## 7. CONTROL LIMITATIONS

The fundamental restrictions that have been identified in the base function “control of processing, storage, transmission of systems and functions” are:

- *Lack of flexibility and adaptive control.* In the current Internet model, design of IP (and more generally communication) control and service components have seen so far being driven exclusively by cost/performance ratio considerations and pre-determined/pre-defined open loop control processes. The first limits the capacity of the system to adapt/react in a timely and cost-effective manner when internal or external events occur that affect its value delivery, referred to as flexibility[7][16][17]. The current trend in unstructured addition of ad-hoc functionality to partially mitigate this lack of flexibility has resulted in increasing complexity but also (operational and system) cost of the Internet. Further, to maintain/sustain (or even increase) its value delivery over time, the Internet will have to provide flexibility in its functional organization, adaptation, and distribution in order to cope with the increasing uncertainty (unattended and unexpected events) as well as variability of expected events/running conditions. The second leaves no possibility for individual systems to adapt their control decisions and tune their execution (at running time) by taking into account its internal state, its activity/behavior as well as the environment/external conditions in order to increase their overall performance, and functionality. [ANA][ SelfNet] [UniverSelf] [ECODE][SOA4ALL]

- *Segmentation of data, services and control.* The current Internet model segments (horizontally) data and control, whereas from its inception control has a transversal component i.e. IP control component applies across layers even those not associated with IP forwarding. For instance, Ethernet hubs can be controlled by Simple Network Management Protocol (SNMP) MIBs. Another example is Generalized Multi-Protocol Label Switching (GMPLS [18]) that defines a unified control paradigm for IP/MPLS altogether with SONET/SDH, WDM, etc. Thus, on one hand, IP functionality isn't limited anymore to the "network layer", and on the other, IP is not totally decoupled to the underlying "layers" anymore (by the fact IP/MPLS and underlying layers share the same control instance). The same also applies to services, which are not only at application layer, but may traverse the protocol stack to get support from the network layer. Hence, the hour-glass model of the Internet does not account for this evolution of the control functionality when considered as part of the design model. [OPTIMIX] [ETICS] [4WAND]

- *Lack of reference architecture of the IP control plane.* The IP data plane is itself relatively simple but its associated control components are numerous and sometimes overlapping (as a result of the incremental addition of ad-hoc control components over time) and thus their interactions more and more complex. This leads to detrimental effects for the controlled entities, e.g., failures, instability, inconsistency (forwarding loops) [19][20].

- *Lack of efficient congestion control.* Congestion control is intended to provide with a set of mechanisms to maintain the stability and efficiency of the Internet. However,

[7] See Section 2 for a definition of flexibility

congestion control cannot be realized as a pure end-to-end function: congestion is an inherent network[8] phenomenon that can only be resolved efficiently by some cooperation of end-systems and the network. There would be substantial benefit by further assistance from the network, but, on the other hand, such network support could lead to duplication of functions, which may harmfully interact with end-to-end protocol mechanisms. Addressing effectively the trade-off of network support without decreasing its scaling properties (by requiring maintenance of per-flow state) is one of the main Internet's challenges [13] [TRILOGY].

- *Support of mobility*: when using IP address as both network and host identifier but also TCP connection identifier results in Transmission Control Protocol (TCP) connection continuity problem. Its resolution requires decoupling between the identifier of the position of the mobile host in the network graph (network address) from the identifier used for the purpose of TCP connection identification. Extending this limitation, when a mobile host enters a new environment it should be able to discover and utilize hosts, services and data offered at this position. A new naming approach could result if simple re-engineering solution would address the problem. Moreover, when mobility is enabled by wireless networks, packets can be dropped because of corruption loss, rendering the typical reaction of congestion control mechanism of TCP inappropriate. As a result, non-congestive loss may be more prevalent in these networks due to corruption loss (when the wireless link cannot be conditioned to properly control its error rate or due to transient wireless link interruption in areas of poor coverage). This limitation results thus from the existence of heterogeneous links, both wired and wireless yielding a different trade-off between performance, efficiency and cost. The idea of having a transport endpoint detecting and accordingly reacting (or not) to corruption poses a number of interesting questions regarding cross-layer interactions (see [RFC6077] for more details).

## 8. LIMITATIONS THAT MAY FALL IN MORE THAN ONE CATEGORIES

Some fundamental limitations of current Internet may fall in more than one category. As an example:

- *Traffic growth vs heterogeneity in capacity distribution:* Hosts connected to the Internet do not have the possibility to enforce the path followed by their traffic; hence even if multiple means to reach a given destination would be offered to the host, they are unable to enforce their decision across the network. On the other hand, as the Internet enables any-to-any connectivity, there is no effective mean to predict the spatial distribution of the traffic within a timescale that would allow providers to install needed capacity when required (or at least expected to prevent overload of certain network segments). This results into serious capacity shortage (and thus congestion) over certain segments of the network. Especially, the traffic exchange points (in particularly the international and the transatlantic links) are in many cases significantly overloaded. In some cases, building out more capacity to handle this new congestion may be infeasible or unwarranted. Moreover the telecom operators

[8] By network we mean here the shared communication infrastructure (the term network is indeed confusing at it can refer to a function to a set shared distributed resources or even to the set of host these resources interconnect).

hesitate to further invest in network infrastructure as there is no mean to obtain direct return on investment. We see two main types of limitations here i) no known scalable mean to overcome the result of network infrastructure abstraction: hiding heterogeneous properties of (diversity of) paths towards hosts, and ii) those related to congestion and diagnosability [TRILOGY][ONELAB2]

- *The current inter-domain routing system is reaching fundamental limits* in terms of routing table scalability but also adaptation to topology and policy dynamics (perform efficiently under dynamic network conditions) that in turn impact its convergence, and robustness/stability properties. Both dimensions increase memory requirements but also processing capacity of routing engines [21][7] [EULER] [ResumeNet].

- *Scaling to deal with flash crowding.* The huge number of (mobile) terminals combined with a sudden peak in demand for a particular piece of data may result in phenomena which can't be handled.

- The amount of foreseen services, data and information[9] requires significant *processing power / storage / bandwidth for indexing / crawling and (distributed) querying* and also solutions for large *scale / real-time data mining / social network analysis*, so as to achieve successful retrieval and integration of information from (numerous) sources across the network. All the aforementioned issues imply the need for addressing new architectural challenges able to cope with fast and scalable identification and discovery of and access to data and services, and to overcome heterogeneities in data and processes. The exponential growth of information makes it increasingly harder to identify relevant information ("drowning in information while starving for knowledge"). This information overload becomes more and more acute and existing search and recommendation tools are not filtering and ranking the information adequately and lack the required granularity (document-level vs. individual information item).

- *Security of the whole Internet Architecture.* The Internet is not intrinsically secure and is based on add-ons (e.g. protocols) to secure itself. Protocols may be secure, but the overall architecture is not self-protected against malicious attacks.

## 9. DESIGN OBJECTIVES

The purpose of this section is to document the design objectives that should be met by the Internet architecture. By "design objectives" we mean here the functional and performance properties as well as the structural and quality properties that the architecture is expected to meet. From the previous sections in their current form, some objectives are met and others are not by the architecture of the Internet. We also emphasize here that these objectives are commonly shared and agreed even if the below text is our initial thoughts on the properties that should be met by the Internet architecture starting from the initial of objectives as enumerated in various references (see [27], [28], [29]).

[9] Eric Schmidt, the CEO of Google, the world's largest index of the Internet, estimated the size at around 5 million terabytes of data (2005). Eric commented that Google has indexed roughly 200 terabytes of that is 0,004% of the total size.

One of the key challenge is thus to determine the additional / improvement of current architecture principles and additional / improvement (or even removal) of architectural components that will eliminate or at least tangibly mitigate/avoid the known effects of these limitations (it is to be emphasized that a great part of research activities in this domain consists in identifying hidden relationships).

## 9.1 High-Level Design Objectives

The high-level design objectives of the Future Internet are listed in this section. This is also in-line with the objectives used in the cross-ETP long-term vision document [29]. Future Internet Architecture should be designed to:

1. Accommodate unanticipated user expectations together with its continuous empowerment.
2. Become the common and global information exchange of human knowledge.
3. Leverage and evolve information and communication technologies as well as capabilities and services to fulfill increased quantity and quality of Internet use (considering the requirements from an increasingly heterogeneous set of applications such as manufacturing, multimedia, healthcare, and power distribution).
4. Be scalable to provide cultural, scientific and technological exchange among different regions and cultures, and within single communities.
5. Be ubiquitously accessible (from physical, to connectivity and informational level), and open (by recognizing that access and use of information as well as associated processing means are common non-discriminatory universal rights).
6. Be secure, accountable, and reliable without impeding user privacy, dignity, and self-arbitration.
7. Support mobility, have widespread ubiquitous coverage, and be capable of assisting society in emergency situations.
8. Support means for various performance adaptability features based on context, content, etc.
9. Support the innovative business models that are emerging (and may emerge in the future) to allow for more entities (including businesses, SMEs, and individuals) to be involved in providing any particular instance of a service.
10. Support complex abstractions for service addressing at the application level for the realization of a service addressing mechanism that is independent from the physical location (and if possible, technology) of the services.
11. Be carbon neutral and sustainable.

## 9.2 Low-Level Design Objectives

The Internet architecture has been structured around eight foundational objectives (see [27]): i) to connect existing networks, ii) survivability, iii) to support multiple types of services, iv) to accommodate a variety of physical networks, v) to allow distributed management, vi) to be cost effective, vii) to allow host attachment with a low level of effort and, viii) to allow resource accountability. Moreover, RFC 1287 (published in 1991 by the IAB [36]) underlines that the Internet architecture needs to be able to scale to $10^9$ networks recognizing the need to add scalability as a design objective. In this context, the followed approach consists of starting from the existing Internet design objectives compared to the approach that would consists of applying a tabula rasa (completely redefine from scratch the Internet design objectives).

Based on previous sections, the present section outlines the design objectives that are currently met, partially met or not met by the current architecture. The low-level design objectives of the architecture are to provide:

- ***Accessibility*** (open and by means of various/heterogeneous wireless/radio and wired interfaces) to the communication network but also to heterogeneous data and services, nomadicity, and mobility (while providing means to maintain continuity of application communication exchanges when needed). Accessibility and nomadicity are currently addressed by current Internet architecture, mobility is still realized in most cases by means of dedicated/separated architectural components (instead of MIPv4 or MIPv6).

- ***Accountability*** (of resource usage and security without impeding user privacy, utility and self-arbitration): see Section.4.Point.2

- ***Manageability*** (distributed, automated, and autonomic operation): see Section.7 and Diagnosability (root cause detection and analysis): see Section.4.Point.1

- ***Transparency*** (the terminal/host is only concerned with the end-to-end service, in the current Internet this service is the connectivity even if the notion of "service" is not embedded in the architectural model of the Internet): initially addressed but loosing ground.

- ***Distribution of processing, storage, and control functionality and autonomy*** (organic deployment): addressed by current architecture (concerning storage and processing several architectural enhancements might be required e.g. for the integration of distributed but heterogeneous data and processes).

- ***Scalability*** (including routing and addressing system in terms number of hosts/terminals, number of shared infrastructure nodes, etc. and management system): - see Section.8.Point.2

- ***Reliability*** refers here to the capacity of the Internet to perform in accordance to what it is expected to deliver to the end-user/hosts while coping with a growing number of users with increasing heterogeneity in applicative communication needs.

- ***Robustness/stability***, resiliency, and survivability: - see Section.8.Point.2

- ***Security***: see Section.8 point 5, Section 6.Point.2 and other.

- ***Genericity*** (e.g. support multiple data traffic such as non/real-time streams, messages, etc., independently of the shared infrastructure partitioning/divisions, independently of the host/terminal): addressed and to be reinforced (migration of mobile network to IPv6 Internet, IPTV moving to Internet TV, etc.) otherwise leading to segmentation and specialization per application/service.

- ***Flexibility*** (capacity to adapt/react in a timely and cost-effective manner when internal or external events occur that affect its value delivery) and Evolutivity (of time variant components): not addressed see Section7.Point.1.

- ***Simplicity and cost-effectiveness***: more data is needed but simplicity seems to be progressively decreasing see 7.3. Note that simplicity is explicitly added as design objective to -at least- prevent further deterioration of the complexity of current architecture (following the "Occam's razor principle" key design principle). Indeed, lowering complexity for the same level of performance and functionality at a given cost is key objective.

- ***Ability to offer information-aware transmission and distribution***. Section.6.Point.1 and Section.8.Point .4

## 10. CONCLUSIONS

Many of the identified fundamental limitations are *not isolated but strongly dependent on each other. Increasing the bandwidth would significantly help to address or mitigate some of these problems, but would not solve the*ir root cause. Other problems would nevertheless remain unaddressed. The ***transmission*** can be improved by utilising better ***data processing & handling*** (e.g. network coding, data compression, intelligent routing) and better ***data storage*** (e.g. network/terminals caches, data centres/mirrors etc.), while the overall Internet performance would be significantly improved by **control & self-*** functions.

As an overall result we may conclude to the following:

***Extensions, enhancements and re-engineering of today's Internet protocols may solve several challenging limitations. Yet, addressing the fundamental limitations of the Internet architecture is a multi-dimensional problem. Improvements in each dimension combined with a holistic approach of the problem space are needed.***

## 11. References


[1] AKARI Project, "New Generation Network Architecture AKARI Conceptual Design (ver1.1)," AKARI Architecture Design Project, Original Publish (Japanese) June 2008, English Translation October 2008, Copyright © 2007-2008 NICT

[2] Francisco Medeiros, "ICT 2010: Digitally Driven", Brussels, 29 September 2010 (Source Cisco VNL, 2010)

[3] P. Mahonen (ed), D. Trossen, D. Papadimitrou, G. Polyzos, D. Kennedy, "Future Networked Society", EIFFEL whitepaper, Dec.2006

[4] Jacobson V, Smetters D., Thornton J., Plass M., Briggs N., Braynard R., "Networking Named Content," Proceeding of ACM CoNEXT 2009. Rome, Italy, December 2009

[5] Moors, T., "A critical review of "End-to-end arguments in system design", Proceedings of IEEE International Conference on Communications (ICC) 2002, New-York City (New Jersey), USA, April/May 2002.

[6] RFC 1958 "The Internet and its architecture have grown in evolutionary fashion from modest beginnings, rather than from a Grand Plan"

[7] T. Li, (Ed.) "Design Goals for Scalable Internet Routing," Work in progress, draft-irtf-rrg-design-goals-02, Sep.2010.

[8] http://www.future-internet.eu/

[9] http://www.nsf.gov/pubs/2010/nsf10528/nsf10528.htm

[10] akari-project.nict.go.jp/eng/overview.htm

[11] mmlab.snu.ac.kr/fiw2007/presentations/architecture_tschoi.pdf

[12] Clark, D. D., Partridge, C., Ramming, J. C., and Wroclawski, J. T. 2003. A knowledge plane for the internet. In Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols For Computer Communications (Karlsruhe, Germany, August 25 - 29, 2003). SIGCOMM '03. ACM, New York, NY, 3-10

[13] D. Papadimitriou, Ed., et al. "Open Research Issues in Internet Congestion Control", Work in progress, draft-irtf-iccrg-welzl-congestion-control-open-research-08.txt, Sep.2010

[14] Akhlaghi S., Kiani A., Reza Ghanavati M., "Cost-bandwidth tradeoff in distributed storage systems, ACM Computer Communications, Volume 33 , Issue 17, Nov. 2010, pg: 2105-2115 (published on-line)

[15] Freedman M, "Experiences with CoralCDN: A Five-Year Operational View," Proc. 7th USENIX/ACM Symposium on Networked Systems Design and Implementation (NSDI '10) San Jose, CA, May 2010.

[16] Dobson S., et al. A survey of autonomic communications. ACM Transactions on Autonomous and Adaptive Systems (TAAS), vol. 1, Issue 2, pp. 223 – 259, 2006.

[17] Gelenbe E. "Steps toward self-aware networks," ACM Communications, Vol.52, No.7 (Jul. 2009), pp.66-75.

[18] E.Mannie, Ed., et al., "Generalized Multi-Protocol Label Switching (GMPLS) Architecture", RFC 3945, October 2004.

[19] Evolving the Internet, Presentation to the OECD, March 2006. Available at http://www.cs.ucl.ac.uk/staff/m.handley/slides/

[20] Re-thinking the control architecture of the internet. Keynote talk, ACM ReArch Workshop 2009 (co-located with ACM CoNext 2009), December 2009.

[21] D.Meyer, et al. Report from the IAB Workshop on Routing and Addressing, IETF, RFC 4984, Sep.2007.

[22] P. Mahonen (ed), D. Trossen, D. Papadimitrou, G. Polyzos, D. Kennedy, "Future Networked Society", EIFFEL whitepaper, Dec.2006

[23] D. Trosse, (Ed.), Invigorating the Future Internet Debate, ACM SIGCOMM Computer Communication Review, Vol.39, No.5, October 2009.

[24] L.Eggert, Quality-of-Service: An End System Perspective, MIT Communications Futures Program – Workshop on Internet Congestion Management, QoS, and Interconnection, Cambridge, MA, USA, October 21-22, 2008

[25] S.Ratnasamy, S.Shenker, and S.McCanne. Towards an evolvable internet architecture. SIGCOMM Comput. Commun. Rev. 35, 4 (August 2005), 313-324.

[26] Cross-ETP Vision Document. Available at <http://www.future-internet.eu/fileadmin/documents/reports/Cross-ETPs_FI_Vision_Document_v1_0.pdf>

[27] D.D.Clark, The Design Philosophy of the DARPA Internet Protocols, Proc SIGCOMM 88, ACM CCR Vol 18, Number 4, August 1988, pages 106-114 (reprinted in ACM CCR Vol 25, Number 1, January 1995, pages 102-111).

[28] J.H. Saltzer,, D.P.Reed, D.D.Clark, End-To-End Arguments in System Design, ACM TOCS, Vol 2, Number 4, November 1984, pp 277-288.

[29] B.Carpenter, Architectural Principles of the Internet, Internet Engineering Task Force (IETF), RFC 1958, July 1996.

[30] B.Krishnamurthy, "I know what you will do next summer", ACM SIGCOMM Computer Communication Review, Oct. 2010, http://www2.research.att.com/~bala/papers/ccr10-priv.pdf

[31] W3C Workshop on Privacy for Advanced Web APIs 12/13 July 2010, London http://www.w3.org/2010/api-privacy-ws/report.html

[32] Workshop on Internet Privacy, co-organized by the IAB, W3C, MIT, and ISOC, 8 and 9 December 2010. http://www.iab.org/about/workshops/privacy/

[33] D.Clark et al, Towards the Future Internet Architecture, Internet Engineering Task Force (IETF); RFC 1287; December 1991.

[34] [ref1] http://www.iso.org/iso/iso_technical_committee.html?commid=45072

[35] [ref2] http://www.itu.int/en/ITU-T/focusgroups/fn/

## 12. Referenced Projects

[4WARD] http://www.4ward-project.eu/

[Alicante] http://www.ict-alicante.eu/

[ANA] http://www.ana-project.org/

[COAST] http://www.fp7-coast.eu/

[COMET] http://www.comet-project.org/

[EIFFEL] http://www.fp7-eiffel.eu/

[EULER] http://www.euler-project.eu/

[IoT-A] http://www.iot-a.eu/

[nextMedia] http://www.fi-nextmedia.eu/

[OPTIMIX] http://www.ict-optimix.eu/

[ResumeNet] http://www.resumenet.eu/

[SelfNet] https://www.ict-selfnet.eu/

[SOA4ALL] http://www.soa4all.eu/

[TRILOGY] http://trilogy-project.org/

[UniverSelf] www.univerself-project.eu

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