

Fundamental Limitations of Current Internet and the path to Future Internet¹

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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 and availability required by these services impose in turn to increase robustness and survivability 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.

All these applications create new demands, which to a certain extent can be addressed through “over-dimensioning”. While the latter can be a satisfactory temporary solution to some cases, analyses have shown [2] 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 like collaborative 3D immersive environments, new commercial and transactional applications, new location-based services and so on.

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.

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In brief, the question is to determine if the architecture itself might become the limiting factor of Internet growth and deployment of new applications. For instance, as stated in [3] “*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 opening the question of its extensibility (but up to which limit?) versus its inherited architectural limits (but up to which extend?). 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, 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: the FIA[4] and the NetSE[5] programs as successors of FIND[6] and GENI [7] in the USA, the AKARI [8] program in Japan and the Future Internet [9] program in Korea. In Europe, a significant part of the Information and Communication Technology (ICT) of the Framework Program 7 has been devoted to FI [10]. Both large/integrated and small/targeted research projects are already running and early results have been published, while the recently launched Private Public Partnership (PPP) program will provide an industry-driven, holistic approach encompassing research, development and innovation on network and communication infrastructures, devices, software, service and media technologies.

The purpose of this document is to identify fundamental limitations of the current Internet and outline 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 formal grouping of a function space, a state space and objects/information, as well as their respective distribution that characterizes their domain.

The specification of the associated functional, object/informational and state models leads to a set of components (i.e. procedures, data structures, state machines, etc.) and the characterization of their interactions (i.e. messages, calls, events, etc.).

We define as "***fundamental limitation***" (of the Internet architecture) a functional 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 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.

Re-engineering" is also defined 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 its global properties.

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.
- "***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. 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 availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance^[4]. It also includes concepts as safety, integrity, conformance, privacy, security, etc. and the concepts of systems' vulnerabilities and failures, along with the way we can minimise 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/services) that generate and treat 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 services, systems and functions.⁴

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 conclusions of those discussion 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:

- *The Internet does not allow hosts to diagnose potential problems and the network offer little feedback for hosts to perform root cause discovery and analysis* [12] On the other hand, the lack of cooperation and misbehavior that may be driven by pure malice or selfish interests are detrimental to (cooperative) Internet users and providers. Non-intrusive and non-discriminatory means to mitigate their effects while keeping open and broad accessibility to the Internet is a crucial limitation to overcome [13].
- *Lack of data identity in the network* is damaging the utility of the communication system. As a result, data, as an ‘economic object’, 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.

⁴ 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”.

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

5. STORAGE LIMITATIONS

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

- *Lack of efficient 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 and storage decisions that guarantee efficient storage management, refreshing and removal optimized for different types of data [14].
- *Lack of inherited data integrity, reliability 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.

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.
- *Security requirements of the transmission links*: It is not sufficient to just protect/encrypt the data (including encryption of protocols/information/content, tamper-proof applications etc), but also protect the communication 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 in control.* In the current Internet model, IP (and more generally communication) control components are driven exclusively by cost/performance ratio considerations leaving very limited (functional) flexibility ⁵[16][17]. Note that the current trend in adding functionality to mitigate this lack of flexibility has resulted in increasing complexity but also (operational and system) cost of the Internet.
- *Segmentation of data 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 over UDP/IP) and Generalized Multi-Protocol Label Switching (GMPLS [18]) defines a unified control paradigm for all sub-IP data layers (e.g. SONET/SDH, WDM, etc). Hence, the hour-glass model does not account for this evolution of the control functionality when considered as part of the design model.
- *Lack of unified architecture of the IP control plane.* The IP data plane is itself relatively simple but its associated control components are numerous (as a result of the incremental addition of ad-hoc components) and thus their interactions more and more complex [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, congestion control cannot be realized as a pure end-to-end function: congestion is an inherent network 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].

8. OPERATIONAL 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:

- *Lack of bandwidth in some network segments:* There are serious limitations in the transmission capacity available in some network segments, significantly increased by the great heterogeneity. Especially the traffic exchange points (in particularly the international and the transatlantic links) are in many cases significantly overloaded. However, the telecom operators hesitate to further invest in network infrastructure as there is no *clear business plan for return on investment*.
- *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,

⁵ See Section 2 for a definition of flexibility

and stability properties. Both dimensions increase memory requirements but also processing capacity of routing engines [21][22].

- *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 data and information 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. *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).*
- *Lack of possibility for the user to express his preference for a service quality* pertaining to his application and his value willingness-to-pay for this.

9. 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 their 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.

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