Considerations on IPv6 Scalability for the Internet of Things – towards an Intergalactic Internet

Sébastien Ziegler
Mandat International
Geneva, Switzerland
sziegler@mandint.org

***Abstract* — This article presents an analytical perspective on IPv6 scalability for addressing the Internet of Things exponentially growing domain. It intends to provide some new perspectives on IPv6 addressing potential for actual and future needs. It leads to a set of clarifications, four conjectures, and a model of intergalactic IPv6 addressing plan.**

***Index Terms* — IPv6, Internet of Things, scalability, addressing, interoperability, conformance, performance, large numbers, intergalactic Internet.**

I. INTRODUCTION

The Internet of Things (IoT) is an ongoing next technological revolution impacting all application domains. It is expected to be massive and pervasive, with over 50 Billion smart things and objects connected by 2020 [1],- and more to come. It will impact many application domains, from agriculture, to smart cites, industry, energy and transportation. The precise number of IoT motes on a longer term is not realistically predictable. However, we can ascertain that it will be massive and growing.

Interoperability has been identified by the International Telecommunication Union (ITU) as a prime requirement for the IoT. The adoption and growth of IoT technology will be directly related to its capacity to overcome its current fragmentation with addressing solutions able to handle very large scale deployments.

In this context, the Internet Protocol version 6 (IPv6) is emerging as the most credible candidate in terms of network protocol. Beyond its global adoption and availability through the Internet, it is characterized by several qualities that constitute a good match to address some of the main Internet of Things requirements:

- Scalability, with 2^128 IP addresses;
- Self-configuration, with its Stateless Address Auto-Configuration Mechanism (SLAAC) [2];
- Mobility;
- Security enablers, such as IPSec;
- Lightweight adaptations IPv6 stack for constraint IoT motes with 6LoWPAN [3], CoAP [4], 6TiSCH [5], etc.;
- Global availability and interconnectivity thanks to the Internet infrastructure;

Over the last decade, the author initiated and was associated to several research projects addressing the convergence between IPv6 and the IoT, including inter alia:

- Universal Device Gateway, a Swiss research project researching the potential of IPv6 to support multiprotocol interoperability for the IoT;
- IoT6, a European research project exploring the potential of IPv6 for the IoT and for cross domain integration;
- Hobnet, a European research project exploring the potential of IPv6, 6LoWPAN and CoAP to support smart buildings;
- IoT Lab, a European research project exploring the potential of Crowdsourcing and IoT for research, as well as the potential of IPv6 to federate heterogeneous IoT testbeds;

While the IoT industry seems to converge towards IPv6, there are still questions related to the effective capacity of IPv6 to address an exploding demand of a massively growing number of communicating devices. The present article intends to provide some clarifications on this matter.

II. IPV6 GENESIS AND STRUCTURE

In 1969, the Advanced Research Projects Agency Network (ARPAnet) interconnected two first networks. In December 1974, the Internet Engineering Task Force (IETF) adopted the RFC 675 [6] on Specification of Internet Transmission Control Program, which forged the term Internet. This RFC was edited by Vinton Cerf, Yogen Dala and Carl Sunshine and was so well designed, that it was not obsoleted before 2016 (by RFC 7805 [7]). A first specification of the Internet Protocol was released in January 1980 (RFC 760) [8] and replaced in September 1981 by the RFC 791 [9], which specified the Internet Protocol Version 4 (IPv4).

The development of the World Wide Web (WWW) by the European Centre for Nuclear Research (CERN) in Geneva [10] and the specification of the Hypertext Transfer Protocol (HTTP) [11], [12] paved the way to a larger use and adoption of the Internet by the industry and by the public at large in the nineties. It led to an exponentially growing demand for Internet Protocol (IP) addresses and forced the IETF to consider and anticipate the exhaustion of the remaining IPv4 addresses.

In 1992, the IETF launched a call for white papers to design a successor to IPv4 leading to the specification in 1995 of the Internet Protocol Version 6 (IPv6) in the RFC 1883 [13], followed by complementary RFCs in 1996. The IPv6 specification was updated three years later, in December 1998, through the adoption of RFC 2460 [14], which constitutes the central and main reference RFC for IPv6.

Despite the large adoption of Network Address Translation (NAT) mechanism [15] by Internet Service Providers (ISPs), in February 2011, IANA had to give away its last IPv4 address blocks to the Regional Internet Registries (RIR) [16]. Subsequently, the RIRs themselves have progressively allocated and exhausted their remaining IPv4 addresses blocks. On April 2011, APNIC allocated its last /8 address block of IPv4 addresses, and was progressively followed by RIPE in September 2012, LACNIC in June 2014 and ARIN in September 2015. AFRINIC is expected to deplete its pool of remaining IPv4 addresses by 2018. As a consequence, the Internet has progressively adopted IPv6 as the only realistic alternative to IPv4 depletion. Currently, both protocols are coexisting on the Internet, with a dual stack IPv4-IPv6 network architecture, and a progressive transfer of traffic from IPv4 to IPv6.

In parallel, IPv6 has rapidly been identified as an interesting technology for the IoT. The IETF community started developing complementary RFCs to address specific IoT requirements. It progressively led to the specification of new IPv6-based standards for the IoT, such as 6LoWPAN [17], RPL [18], CoAP [4], 6TiSCH.

As specified by the IPv6-related RFCs and largely presented in previous articles such as [19], the IPv6 address is sub-divided in two halves, encompassing three distinct segments:

- The Routing Address, which is split in two parts:
  - o The Global Routing Prefix (GRP) assigned to a site;
  - o The Subnet Identifier (Subnet ID) which is managed by the site and enables to differentiate several subnetworks.
- The Interface Identifier (Interface ID or IID, also named Host ID), which corresponds to a specific interface address of an end-node.

As illustrated in Figure 1, the first 64 bits of the address are used for the network routing address, including the GRP and the Subnet ID; and the second half (the remaining 64 bits) is reserved for the Interface ID.

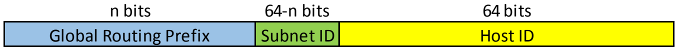

Fig. 1 IPv6 address structure

III. ORDERS OF MAGNITUDE AND LARGE SCALE NUMBERS

In order to assess the scalability of IPv6 addresses, let's identify a few benchmarks in terms of large numbers. There are about:

~4,3 x 10^{9}	IPv4 addresses (2^{32})
~7,3 x 10^{9}	Human beings on earth [20]
~5 x 10^{10}	IoT devices by 2020 [21]
~1 x 10^{11}	Planets in our galaxy
~8,6 x 10^{11}	Neurons in a brain [22]
~2 x 10^{12}	Galaxies in the universe [23]
~5,1 x 10^{14}	Square meters on the Earth surface [24]
~1 x 10^{15}	Synapses in a brain [25]
~7,5 x 10^{18}	Grains of sand on earth [26]
~5,1 x 10^{20}	Square millimetres on the Earth [24]
~3 x 10^{23}	Stars in the universe [27]
~7 x 10^{27}	Atoms in one human body [28]
~5,1 x 10^{37}	Atoms in all human bodies (from the above)
~3,4 x 10^{38}	IPv6 addresses (2^{128})

We can already demonstrate that the theoretical IPv6 addressing capacity is larger than the previous benchmarks. Indeed, we could use IPv6 addresses to each all the mentioned groups of objects and still have sufficient unallocated addresses available to run the Internet.

Let's move towards larger figures. We could consider the mass of the universe, which is estimated to be between 10^{50} and 10^{60} Kg [29]. If we want to extend our scale, we need to move towards purely mathematical figures, such as:

- The Googol, which equals 10^{100} (or 10^100) [30]
- The Googolplex, which equals 10Googol (or $10^{10^{100}}$ or 10^(10^100)) [31]

We can still extend our scale with a few additional numbers, by leveraging on hyperoperations. Let's name and define a few large numbers as follow:

- $10\uparrow\uparrow 10$, as Guillion;
- $100\uparrow\uparrow 100$, as Theillion;
- $1000\uparrow\uparrow 1000$, as Vintillion;
- $10\uparrow^{10}10$, or $10\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow 10$, as Zieglion;
- $F^{10}(10)$, F(F(F(F(F(F(F(F(F(F(10)))))))))), where $F(n) = n\uparrow^{n}n$. We will name it Annilion;
- Finally, let's take in consideration the Graham's number [32].

These last numbers are obviously larger than any ensemble of tangible elements, such as the number of electrons, in the universe. They are tending towards the infinite, but they are still finite.

IV. IPV6 SCALABILITY

Now that we have an extended scale, let's assess the potential of IPv6. The Internet Protocol version 4 (IPv4) uses 32 bits long addresses, which equals to about 4 Billion (4,294,967,296) distinct addresses (2^{32}). In practice, the number of usable addresses is quite lower due to routing requirements and to the history of IPv4 address blocks allocation.

The Internet Protocol version 6 (IPv6) uses 128 bits addresses, which equals to 3.4 $\times 10^{38}$ unique addresses (2^{128}), or 340 undecillions (340 x 10^{36}) addresses. This number of unique IPv6 addresses can be mathematically represented in diverse manners, including 2^{128}, 3.4 $\times 10^{38}$, $2^{2^{7}}$, as well as by using Knuth's up-arrow notation $2\uparrow 128$. We can also represent it through the use of a forth tetration of 2: $(2\uparrow\uparrow 4)^{8}$, which can also be noted with the Maurer (or Rudy Rucker) presentation as $({}^{4}2)^{8}$, where $2\uparrow\uparrow 4$ corresponds to the number of possible combinations in a segment of 4 hexadecimal digits of an IPv6 address.

Multiplying by four the address space seems to be a minor change, but this extension creates a fundamental paradigm shift in terms of scalability. It enables to provide a unique IP address to any device, end-node, and resource. At the level of the Earth, IPv6 addressing capacity is sufficient to provide 6.67126 x 10^{17} unique addresses per square millimetres of Earth surface. Even if we consider only the second half of the IPv6 address, the 64 bits Interface ID, it equals to 3.61 unique IP addresses per square centimetre of the total Earth surface, and 12.39 unique IPv6 addresses per square centimetre of emerged land surface on Earth (if we ignore the oceans).

IPv6 could use single subnet addresses to provide unique Host IDs to each Human beings on earth, each IoT devices, each neuron in a brain, each square meters on the Earth surface, each synapse in a brain, and each grain of sand on earth. It would however require to use part of the Subnet and GRP segment to address all the stars in the universe or all the atoms of a human body.

A. Human Limitations

Another way to approach IPv6 scalability is to adopt a human perspective. Let's consider a single human being who would spend his whole life to allocate IP addresses, at a rate of one IP address every second of his life, days and nights included, from his birth to his 80 years old anniversary. He could allocate about 2'522'880'000 addresses, ~2.5 x 10^9.

Any ISP client subscribing for an IPv6 connection will by default benefit from a global ID and several subnets. A single subnet can generate 2^{64} unique public IP addresses (1.8 x 10^{19}). It is about ten Billion larger (10^{10}) than what a single individual could use over his whole life. In other words, a single subnet is sufficient to occupy non-stop the world population during their whole lives, nights included.

B. IPv6 Scalability Conjectures

By taking into account the limitations related to human capacity to allocate addresses to IoT devices, we will formulate our first conjecture:

IPv6 addressing capacity is sufficient to provide a unique 64 bits Host ID to each and every present and future IoT device on earth and in our solar system, as well as to each individual human and machine Internet user.

Our second conjecture states that:

Mankind will never be able to use and exhaust the complete potential of IPv6 addressing capacity, as long as the address block allocation is aligned with effective needs of end-users (i.e. limiting GRP allocation to /56 or /48).

Our third conjecture states that:

IPv6 addressing capacity is sufficient to provide a unique complete 128 bits address to each and every star in the universe, but would either require an extended Network GRP or a NAT architecture to address large deployments of IoT in each stellar system.

Our fourth conjecture states that:

IPv6 addressing capacity is sufficient to address effective mankind requirements, but can be theoretically superseded by identifiers allocation in mathematical models based on hyperoperations tending towards very large results domains, such Googols, Googolplex, Guilions, Vintillions, Zieglions, Anilions and Graham number.

V. GALACTIC AND INTERGALACTIC ADDRESSING SCHEMES PROPOSAL

It is also possible to consider adapting IPv6 address structure to very large scale deployment, beyond human direct use and exploitation. In order to illustrate our proposition, let's consider and sketch potential schemes for consistent galactic and intergalactic IPv6 addressing plans. We will voluntarily set aside the time constraints of such long distance communications. The NASA estimates that our galaxy gathers about 100 Billion planets [33]. In our theoretical model, we suggest reserving a first block or 48 bits for a Global Routing Prefix for each planet in our galaxy as illustrated in Figure 2. Each planet can then allocate 16 bits for subnets, leaving the complete 64 bits IPv6 Host ID fully available.

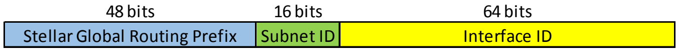

Fig. 2 Galactic IPv6 Addressing Scheme

Let's move farther and see if we can extend IPv6 addressing scheme to the universe. The NASA estimates the number of galaxies in the universe to be close to 2 x 10^{12}. As illustrated in Figure 3, we suggest allocating the first segment of 48 bits for a galaxy routing prefix. With an average of 1.5 x 10^{11} stars per galaxy, and an anticipated variability among galaxies, we suggest allocating another segment 48 bits for the star routing prefix. We can then use the remaining 32 bits for border routers identifiers (or single node identifiers). This would enable to allocate to each star an addressing capacity equivalent to the current IPv4-based Internet.

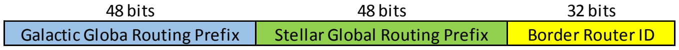

Fig. 3 Intergalactic IPv6 Addressing Scheme

VI. CONCLUSION

Our article intended to provide a complementary perspective on IPv6 scalability. We demonstrated that IPv6 addressing capacity is largely sufficient to satisfy all present and future needs for human-to-human and machine-to-machine communication at the scale of mankind. A condition is however required. We must adopt an efficient address blocks allocation and avoid repeating the mistakes made with IPv4 at the beginning of the Internet.

Acknowledgments: This article has been written in the context of research activities developed by the author in relation with various research projects mentioned in the article, including IoT6, IoT Lab, and F-Interop. The content and the illustrations have been developed in the context of a thesis and are shared in this article.

VII. REFERENCES

[1] « CEO to shareholders: 50 billion connections 2020 », Ericsson.com, 13-avr-2010, at: https://www.ericsson.com/news/1403231.

[2] T. Narten, S. Thomson, et T. Jinmei, « RFC 4862 - IPv6 Stateless Address Autoconfiguration » at: https://tools.ietf.org/html/rfc4862.

[3] N. Kushalnagar, G. Montenegro, et C. Schumacher, « RFC 4919 - IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals » at: http://www.rfc-editor.org/rfc/rfc4919.txt.

[4] Z. Shelby, K. Hartke, et C. Bormann, « RFC 7252 - The Constrained Application Protocol (CoAP) » at: https://tools.ietf.org/html/rfc7252.

[5] IETF, « IPv6 over the TSCH mode of IEEE 802.15.4e (6tisch) - » at: https://datatracker.ietf.org/wg/6tisch/charter/.

[6] Vinton Cerf, Yogen Dalal, et Carl Sunshine, « RFC 675 - Specification of Internet Transmission Control Program » at: https://tools.ietf.org/html/rfc675.

[7] « RFC 7805 - Moving Outdated TCP Extensions and TCP-Related Documents to Historic or Informational Status » at: https://tools.ietf.org/html/rfc7805.

[8] « RFC 760 - DoD standard Internet Protocol » at: https://tools.ietf.org/html/rfc760.

[9] J. Postel, « RFC 791 - Internet Protocol » at: https://tools.ietf.org/html/rfc791.

[10] « CERN - European Organization for Nuclear Research » at: https://home.cern.

[11] J. C. Mogul, J. Gettys, T. Berners-Lee, et H. Frystyk, « RFC 2068 - Hypertext Transfer Protocol -- HTTP/1.1 » at: https://tools.ietf.org/html/rfc2068.

[12] R. Fielding, J. Gettys, J. Mogul, H. Frystyk, L. Masinter, P. Leach, T. Berners-Lee, « RFC 2616 - Hypertext Transfer Protocol -- HTTP/1.1 » at : https://tools.ietf.org/html/rfc2616.

[13] S. Deering et R. Hinden, « RFC 1883 - Internet Protocol, Version 6 (IPv6) Specification » at : https://tools.ietf.org/html/rfc1883.

[14] Stephen E. Deering, « RFC 2460 - Internet Protocol, Version 6 (IPv6) Specification » at: https://tools.ietf.org/html/rfc2460.

[15] P. Francis et K. Egevang, « RFC 1631 - The IP Network Address Translator (NAT) » at: https://tools.ietf.org/html/rfc1631.

[16] « IPv4 Address Report », Potaroo.net, 26-déc-2016. at: http://www.potaroo.net/tools/ipv4/.

[17] P. Thubert et J. W. Hui, « RFC 6282 - Compression Format for IPv6 Datagrams in Low Power and Lossy Networks (6LoWPAN)», at: https://tools.ietf.org/html/rfc6282.

[18] Tim Winter, « RFC 6550 - RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks ». [En ligne]. Disponible sur: https://tools.ietf.org/html/rfc6550.

[19] S. Ziegler, C. Crettaz, et I. Thomas, « IPv6 as a Global Addressing Scheme and Integrator for the Internet of Things and the Cloud », in 2014 28th International Conference on Advanced Information Networking and Applications Workshops, 2014, p. 797‑802.

[20] « World population trends | UNFPA - United Nations Population Fund » at: http://www.unfpa.org/world-population-trends.

[21] L. M. Ericsson, « More than 50 billion connected devices », White Paper, 2011.

[22] « How Many Neurons Are in the Brain? » at: https://www.verywell.com/how-many-neurons-are-in-the-brain-2794889.

[23] « Hubble Finds 10 Times More Galaxies Than Thought », NASA, 13-oct-2016 at: https://www.nasa.gov/feature/goddard/2016/hubble-reveals-observable-universe-contains-10-times-more-galaxies-than-previously-thought.

[24] « Earth - Wikipedia », at: https://en.wikipedia.org/wiki/Earth.

[25] « Total Number of Synapses in the Adult Human Neocortex ». .

[26] R. Krulwich, « Which Is Greater, The Number Of Sand Grains On Earth Or Stars In The Sky? : Krulwich Wonders... : NPR », 17-sept-2012.

[27] « Number Of Stars In The Universe Could Be 300 Sextillion, Triple The Amount Scientists Previously Thought: Study », Huffington Post, 01-déc-2010.

[28] « Composition of the human body - Wikipedia ». at: https://en.wikipedia.org/wiki/Composition_of_the_human_body..

[29] « Mass of the Universe » at: http://hypertextbook.com/facts/2006/KristineMcPherson.shtml.

[30] « Googol », Wikipedia. 13-janv-2017.

[31] « Googolplex », Wikipedia. 05-janv-2017.

[32] « Graham's number », Wikipedia. 04-janv-2017.

[33] « Study Shows Our Galaxy Has at Least 100 Billion Planets », NASA - Jet Propulsion Laboratory, 11-janv-2012, at: http://www.jpl.nasa.gov/news/news.php?release=2012-010.