AN EXPANSIONARY APPROACH FOR THE ALLOCATION OF NEXT GENERATION IPv6 INTERNET ADDRESSES

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by

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LIST OF ABBREVIATION

AfriNIC	Africa Network Information Centre
APNIC	Asia Pacific Network Information Centre
ARIN	American Registry for Internet Numbers
ARPANET	Advanced Research Project Agency Network
AS	Autonomous System
ASO	Address Supporting Organization
BGP-4	Border Gateway Protocol version-4
CIDR	Classless Inter-Domain Routing
CIR	Community Internet Registry
DARPA	Defense Advanced Research Project Agency
DFP	Default Free Prefixes
DFZ	Default Free Zone
DNS	Domain Name System
DoD	Department of Defense
EIGRP	Enhanced Interior Gateway Routing Protocol
FARA	Forwarding directive, Association, and Rendezvous Architecture
FIB	Forward Information Base
GCAP	Global Common Address Pool
GCAR	Global Common Address Registry
GSE	Global, Site, and End-System
IAB	Internet Architecture Board
IANA	Internet Assigned Numbers Authority
ICANN	Internet Corporation for Assigned Names and Numbers
IESG	Internet Engineering Steering Group
IETF	Internet Engineering Task Force
IGP	Internet Governance Project
ILNP	Identifier, Locator Network Protocol
IPng	Internet Protocol next generation
IPv6	Internet Protocol version 6
IR	Internet Registry
IS-IS	Intermediate System to Intermediate System
ISOC	Internet Society
ISP	Internet Service Provider

ITU	International Telecommunication Union
LACNIC	Latin America and Caribbean Network Information Centre
LAN	Local Area Network
LIR	Local Internet Registry
LISP	Locator/ID Separation Protocol
NAT	Network Address Translator
NIR	National Internet Registry
NRO	Number Resource Organization
NSFNET	National Science Foundation Network
OSPF v2	Open Shortest Path First version 2
PA	Provider Aggregatable
PI	Provider Independent
QoS	Quality of Service
RFC	Request for Comments
RIB	Routing Information Base
RIP v2	Routing Information Protocol version 2
RIPE NCC	Réseaux IP Européens Network Coordination Centre
RIR	Regional Internet Registry
ROAD	Routing and Addressing
Shim6	Site Multihoming by IPv6 Intermediation
TCP/IP	Transmission Control Protocol/Internet Protocol
TE	Traffic Engineering
VLSM	Variable Length Subnet Mask
WAN	Wide Area Networks

SUATU PENDEKATAN EKSPANSIONARI BAGI PERUNTUKAN PENGALAMAT INTERNET IPv6 GENERASI AKAN DATANG

ABSTRAK

Tesis ini menunjukkan bahawa 'penyahpusatan lanjut bagi peruntukan Pengalamat Internet IPv6 Generasi Akan Datang adalah mungkin tanpa memberi kesan terhadap kebolehskalaan (scalability) dan kestabilan sistem laluan Internet.' Ia menjelaskan suatu 'Pendekatan Ekspansionari' dan 'Model Implementasi' yang memungkinkan penyahpusatan yang sedemikian.

Pada masa ini, pengagihan pengalamatan Protokol Internet versi 6 (IPv6) adalah mengikut hierarki tunggal dengan satu kuasa terpusat atasan dan sebahagian kuasa desentralisasi ke bawah. Pengagihan pengalamatan IPv6 hierarki tunggal menghalang pilihan pengguna dengan kuasa pengagihan alamat menjadi satu monopoli. Sesetengah anggota dalam komuniti internet yang bersuara bertentangan dengan sistem pengagihan alamat IPv6 yang ada mencari penyelesaian alternatif. Hasilnya, usul-usul telah dibuat oleh penyelidik-penyelidik bahawa model abstrak menyokong desentralisasi. Pengenalan penyahpusatan selanjutnya, memungkinkan monopoli Daftar Internet Wilayah (Regional Internet Registries, RIR) yang sedia ada disingkirkan bagi menjana kompetitif dalam kalangan entiti sebaya. Suatu persekitaran yang kompetitif dengan peruntukan bagi memilih pelbagai sumber untuk mendapatkan pengalamat IPv6 akan memberi manfaat kepada pengguna, iaitu dari segi perkhidmatan yang terbaik atau yang lebih berkesan.

Wujud keprihatinan terhadap cadangan atau proposal tentang pelbagai hierarki atau sistem alternatif daripada peruntukan alamat IPv6. Alasan tentang wujudnya keprihatinan ini adalah bahawa skema peruntukan wilayah semasa sudah berada pada tahap penyahpusatan yang optimum. Jadi, sebarang penyahpusatan selanjutnya akan mendorong berlakunya penyerpihan atau fragmentasi alamat yang mengakibatkan peningkatan dalam saiz jadual

laluan teras Internet, yang akhirnya akan memberi kesan terhadap kestabilan dan kesinambungan Internet. Oleh itu, tesis ini menunjukkan bahawa kepercayaan di atas adalah tidak betul atau falasi.

Pendekatan Ekspansionari yang dicadangkan, dibina atau dibangunkan berdasarkan merit model abstrak yang merupakan suatu tambahan bagi sistem peruntukan alamat IPv6 sedia ada. Dalam pendekatan ini, suatu daftar alamat diperkenalkan, yang bertindak sebagai suatu ‘entiti sebaya’ bagi RIR sedia ada. titi ini sebagai suatu alternatif, kemudiannya akan mewakili pengalamat IPv6 bagi pengguna yang memerlukannya. Satu Implementasi Pendekatan Ekspansionari dikenali sebagai ‘Model Daftar Internet Komuniti [(Community Internet Registry, CIR) model],’ yang dijelaskan dalam tesis ini. Pendekatan Ekspansionari menggunakan keseluruhan ruang alamat *global unicast IPv6* sebagai sumber atau tempat penjanaan peruntukan alamat IPv6. Ruang alamat ini merupakan suatu saiz yang besar jika dibandingkan dengan kolam alamat wilayah yang digunakan pada masa ini. Pendekatan Ekspansionari yang, digandingkan dengan algoritma peruntukan alamat sedia ada, membolehkan segala peruntukan awal berkembang secara contiguously, bagi mengelak daripa berlakunya penyerpihan atau fragmentasi alamat.

Pada masa akan datang, IPv6 akan berdepan dengan pertumbuhan yang tidak dijangkakan terutamanya dalam perkomputeran dan Internet. Perkara ini boleh menyebabkan algoritma peruntukan alamat mengekang peruntukan awal daripada berkembang. Dalam situasi yang sedemikian, suatu ‘algoritma peruntukan alamat hibrid’ diperkenalkan di dalam tesis ini, yang akan menjadi suatu penambahbaikan yang amat berkesan bagi algoritma peruntukan-alamat sparse dalam meminimumkan penyerpihan atau fragmentasi.

Keputusan daripada eksperimen matematik dan simulasi menunjukkan bahawa Pendekatan Ekspansionari yang dicadangkan secara teknikalnya adalah mungkin. Ia menghapuskan atau meminimumkan penyerpihan atau fragmentasi alamat, dengan cara memaksimumkan pengagregatan alamat, berbanding dengan pendekatan peruntukan alamat IPv6 sedia ada. Oleh itu, Pendekatan Ekspansionari tidak memberi impak atau mengancam kebolehskalaan atau kestabilan Internet. Pendekatan yang dicadangkan merupakan suatu ‘mekanisme kelestarian bagi penyahpusatan lanjut daripada Pengalamat Internet IPv6 Generasi Akan Datang’

AN EXPANSIONARY APPROACH FOR THE ALLOCATION OF NEXT GENERATION IPv6 INTERNET ADDRESSES

ABSTRACT

This thesis shows that ‘further decentralization for the allocation of Next Generation IPv6 Internet Addresses is possible without affecting the scalability and stability of the Internet routing system.’ It describes an ‘Expansionary Approach’ and an ‘Implementation model’ that allows for such decentralization.

Currently, the allocation of Internet Protocol version 6 (IPv6) addresses follows a single hierarchy with a centralized authority at the top and some level of decentralization towards the bottom. Single hierarchy for IPv6 address allocation restricts user’s choice with the address allocation authority becoming a monopoly. Some members of the Internet community have voiced against the present system of IPv6 address allocation seeking for alternative solutions. In response to this, proposals have been made by researchers that are abstract models favoring further decentralization. Introducing further decentralization would remove existing monopoly of the Regional Internet Registry’s (RIRs), thereby creating competitiveness among the peers. A competitive environment with the provision to choose among multiple sources to obtain IPv6 addresses would benefit the users in terms of better or more efficient services.

Concerns have been raised against proposals on alternative systems of IPv6 address allocation by the main advocates of the present address allocation model. The reasons for such concerns were that the current regional allocation scheme is already at optimal level of decentralization. And, any further decentralization would lead to address fragmentation resulting in increased size of the Internet core routing tables, thereby affecting the stability and continuity of the Internet. This thesis shows that the above belief is a fallacy.

The proposed Expansionary Approach is built on the merits of abstract models that are an extension of the present system for IPv6 address allocation. In this approach, an address registry is introduced that acts as a ‘peer entity’ to the existing RIRs. The peer entity as an alternative, would then delegate IPv6 addresses to requesting users. One implementation of the Expansionary Approach called the ‘Community Internet Registry (CIR) model,’ is defined in this thesis. The Expansionary Approach uses the entire global unicast IPv6 address space as the source from which IPv6 address allocation will be made. This address space is massive in size when compared with the regional address pool that is currently used. The Expansionary Approach, coupled with the existing sparse address allocation algorithm, allows an initial allocation to grow contiguously, eliminating address fragmentation far into the future.

IPv6 in the future may face an unprecedented growth due to ‘ubiquitous computing’ and ‘Internet of things.’ This may constrain the sparse address-allocation algorithm in allowing an initial allocation to grow contiguously after a foreseeable future. In such an eventuality, a ‘hybrid address allocation algorithm,’ introduced in this thesis, would be an efficient improvement over the sparse address allocation algorithm in minimizing fragmentation.

Results from mathematical and simulation experiments indicate that the proposed Expansionary Approach is technically feasible. It eliminates or minimizes address fragmentation, by maximizing address aggregation, far into the future when compared to the existing approach of IPv6 address allocation. As such, the Expansionary Approach does not impact or threaten the scalability or stability of the Internet. The proposed Expansionary Approach is a ‘sustainable mechanism for further decentralization of the allocation of Next Generation IPv6 Internet Addresses.’

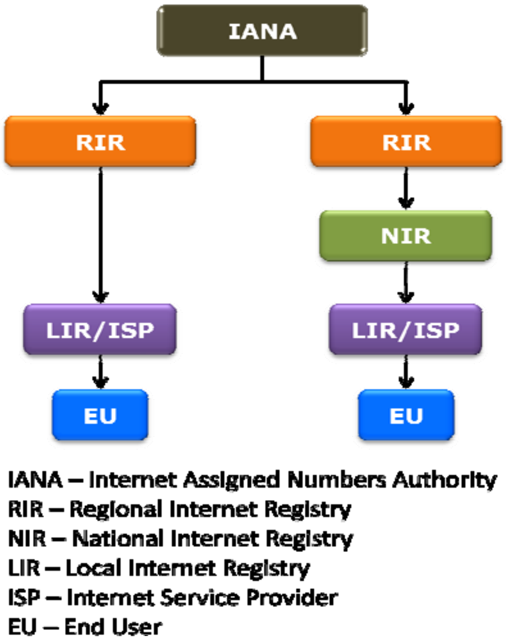
CHAPTER 1
INTRODUCTION

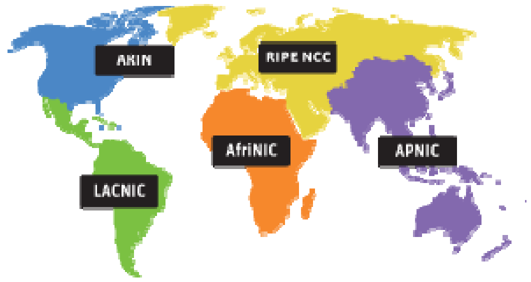
It's not what you don't know that'll get you. It's what you do know that ain't true.
- Mark Twain.

The purpose of this thesis is to demonstrate that *further decentralization for the allocation of Next Generation IPv6 Internet addresses is possible without affecting the scalability and stability of the Internet routing system*. This thesis describes an 'Expansionary Approach' and an 'Implementation model' that allows for such decentralization.

The proposed 'Expansionary Approach' for the allocation of Next Generation Internet Protocol version 6 (IPv6) addresses is created by putting together and building on a couple of existing techniques on IPv6 address allocation that were abstract models. In this 'Expansionary Approach', an address registry is introduced that acts as a peer entity to the existing Regional Internet Registries (RIRs). The peer entity as an alternative would then delegate IPv6 address blocks to requesting users down the address allocation hierarchy.

The Internet number resources, namely IPv6 addresses, are allocated or distributed in a delegated hierarchical fashion. The Internet Assigned Numbers Authority (IANA) as the central authority allocates IPv6 address space on a regional level through RIRs to Internet Service Providers (ISPs) and Local Internet Registries (LIRs) (IANA, 2010b; NRO, 2009). Currently there are five RIRs each serving their own region. The general structure of IP address management hierarchy and the respective regions the five RIRs serve are as shown in Figure 1.1 (IANA, 2010a).





Registry	Area Served
AfriNIC	Africa Region
APNIC	Asia Pacific Region
ARIN	North America Region
LACNIC	Latin America and some Caribbean Islands
RIPE NCC	Europe, the Middle East, and Central Asia

Figure 1.1: IP address management hierarchy and the area RIRs serve globally

There has been strong contention and obscure notions that the current regional address allocation scheme is the maximum or optimal level of decentralization and any further decentralization would be counterproductive in terms of ‘address aggregation’ and hence the ‘scalability’ of the routing system (ISOC, 2009; ITU, 2009). This technical argument, mystifying to the Internet community, has become set in a rigid conventional belief. The perceived threats are much greater than the benefits (Anderson and Rainie, 2010). The assertion was that alternative IPv6 address allocation schemes would increase the number of addresses entering the Internet core routing system. This increase in the number of addresses, a result of splitting a large allocated address prefix into smaller prefixes is called ‘fragmentation’ (opposite to aggregation). The number of addresses entering the Internet core routing system must be within the current capabilities of the routers. Otherwise, it may constrain the routers memory and processing capabilities, thus affecting their stable operation. This thesis falsifies the belief that *the current regional allocation scheme is the maximum or optimal level of* *decentralization and any further decentralization would be counterproductive in terms of 'address aggregation' and hence the 'scalability of the routing system'.*

1.1 Background

The Internet today has evolved from a research-based closed network to a critical, public and commercial infrastructure used by all. The Internet has no centralized control on technological implementations or policies for access and usage, where each constituent network sets its own standards. A network may have controlled access through a user identification and password. The Internet does not have any such framework; and its connectivity is readily shared (Zittrain, 2008). Then *who governs the Internet*? It operates by self-governance influenced by market mechanisms, ISPs, government agencies, regulatory bodies, businesses, associations, standard setting organizations, network engineers, end users etc.

The Internet Protocol (IP) address space and the Domain Name System (DNS) are the only two resources in the Internet being globally coordinated or managed by a centralized organization namely, Internet Assigned Numbers Authority (IANA) operated now by the Internet Corporation for Assigned Names and Numbers (ICANN) (2002). The Internet architecture evolution and its smooth operation that includes the standardization of the Internet Protocol version 4 and 6 (IPv4 and IPv6) are the concern and activity of the Internet Engineering Task Force (IETF). Where, the IETF is a large open international community of network designers, operators, vendors, and researchers.

> *As the Internet becomes ubiquitous and increasingly important in commerce and politics, it will become increasingly important and profitable to control it.*
>
> Benjamin Mordecai Ben-Baruch (Anderson and Rainie, 2010)

Recently, IPv6 address management has attracted greater interest and discussion after proposals were made to introduce competition by having an alternative (choice) to the existing system of IPv6 address distribution. Concerns has been raised by some developing economies and members of the Internet community that the present system of IPv6 address allocation is not adequate and does not meet the growing demands and use of the Internet as a necessary public infrastructure, seeking for alternative solutions. The concerns include technical, economical, and political issues governing the functioning and use of the Internet. Specific issues of substance and that have gained significance are:

i. Increasing size of the Internet core routing tables, and the growth rate can possibly exceed the available router technology at constant cost (Shue, 2009; RFC4984, 2007; Shue and Gupta, 2007).

ii. Ensure equitable distribution of IPv6 address resource and access for all into the future (WGIG, 2005) so that the history does not repeat as with imbalances in IPv4 address allocations.

iii. IPv6 address space is large but not infinite. Though IPv6 is at the early stage of deployment, need to conserve IPv6 address space by avoiding the existing liberal allocation of enormous unit size to avoid premature address exhaustion. *From a public policy perspective, there is a risk to create, yet again, an early adopter reward and a corresponding late adopter set of barriers and penalties* (Millet and Huston, 2005).

Currently, the IPv6 address allocation follows a single hierarchy with a centralized authority at the top and some level of decentralization towards the bottom. A single hierarchy arrangement restricts the user's choice in obtaining their IPv6 addresses. Researchers have voiced their concern over the existing centralized regime at the top of the Internet number allocation hierarchy (Mueller, 2002; Kleinwachter, 2004; Johnson *et al*., 2004; Auerbach, 2004; Maclean, 2004). The concerns identified above among others have been the motivation to define alternative IPv6 address allocation schemes (as an option to the existing system of IPv6 address allocation) by researchers favouring further decentralization (Zhao, 2004; Klein and Mueller, 2005; Mueller, 2006). The impetus for change is said to be from institutional and political rivalries between ICANN and International Telecommunication Union (ITU) (Mueller, 2006; Simon, 2006; Rony and Rony, 1992). While fairly the rationale for these proposals is that the introduction of competition will naturally lead to better or more efficient services to the users.

Understanding the evolution of the Internet and its address space will help us to appreciate the decentralization of the Internet address space and its importance. Later, this would provide motivation indicating the importance of further decentralizing the Internet address distribution.

1.1.1 The Internet and Internet Addressing

The Internet architecture requires a global addressing mechanism called Internet or IP address for a computer in a network to identify and communicate with computers within or on any other network (Khan and Cerf, 1999). *IP addresses* are unique numeric identifiers for a computer or a device on the Internet. It includes information on how to reach a network location through the Internet routing system. Addressing refers to how, hosts become assigned IP addresses and how subnets or sub-networks of IP host addresses are divided and grouped together.

Currently, two versions of the IP are in use, IPv4 and IPv6. IPv4 is the first major version of addressing scheme and is still dominant in use. It was designed to support up to 4.3 billion (4.3×10^9) Internet hosts. However, the explosive growth of the Internet has led to IPv4 address exhaustion. The projected IANA and RIR unallocated IPv4 address pool exhaustion is predicted as 01-Feb-2011 and 15-Aug-2011 respectively (Huston, 2011). The successor addressing scheme IPv6, developed in the mid 1990s, is being deployed actively worldwide. It provides a very large addressing capability of 340 undecillion (3.4×10^{38}) addresses and a more efficient routing of Internet traffic.

A review on Internet Addressing and Routing, including an overview of the version history of IP addresses, is given in Chapter 2.

1.1.2 The Early Internet Address Distribution Model

From the inception of the Internet, devices needed an IP address to identify and communicate with each other over the network. To ensure uniqueness, IP addresses must be allocated and registered in an organized manner. Since the inception of the Internet, one man Jon Postel (Karrenberg *et al*., 2001; RFC790, 1981) who recorded the work in a paper notebook did this task of global IP address registry. But, as the workload and number of requests for IP addresses became too large for an individual to handle this important role was formalized as IANA. Figure 1.2 shows the centralized allocation of IP addresses by IANA prior to the existence of the RIRs.

Until 1992, the IPv4 address space assignment was made centrally by IANA managed by Jon Postel, the ‘number czar’ (RFC349, 1972). This includes both the early version of the IP address and ‘classful’ IPv4 addresses, which were assigned in an arbitrary fashion roughly according to the size of the organizations requested. All address assignments were essentially flat and recorded centrally. No attempt was made to assign addresses in a way that would allow routing aggregation (RFC4632, 2006).

This situation eventually resulted in the historical geographical imbalance of IPv4 address allocation.

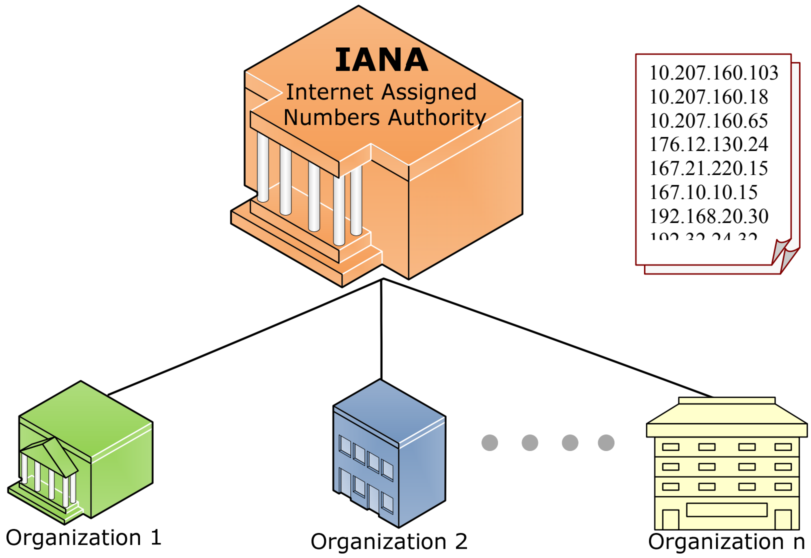


Figure 1.2: Centralized allocation of IP addresses

1.1.3 The Current Decentralized Internet Address Distribution Model

In the 1990's, as the Internet quickly grew and spread across the world, IANA was unable to scale to meet the demands for addresses as well as varied regional needs (Karrenberg *et al.*, 2001). Also, it became painfully evident that the phenomenal growth of the Internet extending to every continent from the purview of pure R&D establishments led to routing and scaling problems. This was mainly due to technical imbalance of IP address allocation and the Internet followed a flat architecture. In 1992, the Internet Engineering Steering Group (IESG) provided a preliminary report of its deliberations as how routing and addressing issues can be pursued in the Internet Architecture Board/Internet Engineering Task Force (IAB/IETF) (RFC1380, 1992). As an interim measure to solve the Internet routing scaling problem, the concept of 'supernetting' or 'route aggregation' (RFC1338, 1992), Classless Inter-Domain Routing (CIDR) (RFC4632, 2006) and architecture for address allocation with CIDR respectively were defined (RFC1518, 1993). These mechanisms need to follow a hierarchy that demands an address distribution function to be decentralized. Decentralization would facilitate address assignment to follow the topology of the network as defined by the service providers. The intention was to make possible the aggregation of routing information along topological lines.

Aggregation was seen as a temporary solution to slow down the routing table growth to provide a scalable inter-domain routing. So, Fuller *et al.* (RFC1388, 1992) introduced a scheme of distributing the allocation of Internet address space by following a hierarchy which would facilitate aggregation. This was the technical reason for which the address distribution function was decentralized.

In 1992, the IETF recommended that Internet number resources should be managed regionally (RFC1366, 1992). In the same year, decentralization began with the delegation of address space assignment to European Internet Sites were made to Rêseaux IP Européens Network Coordination Centre (RIPE NCC) followed by Asia Pacific Network Information Centre (APNIC) in 1993, and American Registry for Internet Numbers (ARIN) in 1997. Later, Latin American and Caribbean Internet Addresses Registry (LACNIC) in 2002 and African Network Information Center (AfriNIC) in 2005 were recognized as RIRs. The RIRs emerged to take on this role for their respective regional communities in cooperation with the IANA. Today the five RIRs act collectively on matters relating to the interest of the RIRs and have established the Number Resource Organization (NRO) in Oct 2003 (NRO, 2010). Figure 1.3 shows the current decentralized distribution of IP addresses.

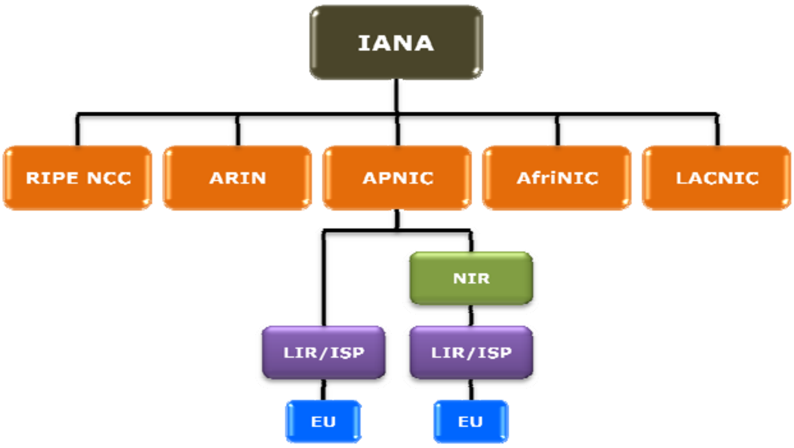


Figure 1.3: Decentralized distribution of IP addresses

Apart from the technical need, it was realized that the administration mechanism of the Internet address distribution need to be further developed (Karrenberg *et al.*, 2001). The method of flat address allocations followed by the early model of Internet address distribution imposed a large bureaucratic cost on the central allocation authority. Distributing the address allocation procedure greatly reduces the load on the central authority, in this case, the IANA. The efficiency and response time for new address assignments greatly improved as the bottleneck of a single organization having responsibility for the global, Internet address space was removed (RFC4632, 2006). The introduction of the decentralized administration in the Internet enhanced the rapid growth of the Internet in the 1990's (Handley, 2006). The technical and administrative reasons were the impetus to decentralization and distribution of the address allocating procedures. Reduced cost and administrative overhead, increased efficiency of operations, response to varied regional needs, and rapid growth of the Internet are merits of decentralization.

1.2 Problem Statement

There are two essential requirements towards the allocation of IPv6 addresses for the reliability and continuity of the proper functioning of the Internet. The first is the ‘technical requirement’ mainly focusing on ‘routing aspects’ within and between domains (RFC1518, 1993). The second is the ‘administrative requirements’ for obtaining and allocating IPv6 addresses. Address fragmentation or de-aggregation is the main cause for increased growth of the Internet core routing tables and therefore degrades scalability. Internet ‘routing scalability’ is an important issue as it directly influences the ‘stability’ and ‘performance’ of the Internet. Routing convergence difficulties because of excessive router-resource consumption to process routes is the cause for network instability (RFC2791, 2000).

Fragmentation is the major concern for routing scalability, and is a challenge to Internet addressing and routing. Poor address allocation policy is one major contributor to address space fragmentation. Existing address allocation practices are a major contributor to address fragmentation. IP address allocation and management, and the scalability of the routing system are interrelated and only certain IP address allocation and management polices yield scalable routing (RFC2008, 1995). Therefore, address aggregation and route aggregation are important for routing scalability; can only be realized by following proper address allocation schemes and management.

The evolution of the Internet exhibits increased decentralization, moving from centralized control to self-governance. IPv6 address allocation presently follows a single hierarchy. In the complete absence of competition, the Internet has a tendency to drift towards a monopoly (Honney, 2002). *The RIRs are a monopoly* (RIPENCC, 2004). Monopolies have market power that leads to missed opportunity in terms of increased output and lower prices provided by a competitive environment. A consumer can usually reduce his service cost due if he can make a choice among suppliers.

Proposals made by some members of the Internet community to further decentralize IPv6 address allocation where rejected by the main advocates of the existing address allocation model. These proposols were abstract models (Zhao, 2004; Klein and Mueller, 2005; Mueller, 2006), required technical and implementation details, did not proceed further as they where letdown with strong contentions. Concerns have been raised against such proposals on multiple hierarchies or alternative systems of IPv6 address allocation claiming that they would affect the scalability and stability of the Internet routing system.

In attempting to refute the above statement, certain questions that are important, interesting, and worthy of research arise. They are summarized as follows:

i) Whether "further decentralization of the Internet number resource distribution is technically possible?"

ii) The above question i) must also examine whether "the current level of regional Internet number resource distribution is the maximum or an optimal level of decentralization."

iii) Scalability is a critical aspect of Internet routing infrastructure. Route aggregation was introduced to contain the growth of the Internet core routing tables. The Internet still exhibits a high level of routing instability despite this increased emphasis on aggregation. Therefore, "is route aggregation still effective and relevant?"

iv) Neither, the bisection nor sequential address allocation algorithms currently used by the RIRs may guarantee address aggregation in the long run (on a worst-case basis in terms of an unexpected and unprecedented growth of IPv6). What could be a plausible alternative or solution that could efficiently handle address aggregation far into the future?

v) Internet addressing and routing are intrinsically related and dependent on each other. The manner in which addresses are sized and distributed in the network directly impacts critical aspects of routing. “What development needs to be made with the address allocation scheme to accommodate further decentralization of the IPv6 address distribution function without affecting the scalabilty and stability of the Inernet routing system?”

Based on the above questions, *an expansionary approach for further decentralization and allocation of Next Generation IPv6 Internet Addresses and an implementation model that allows for this decentralization is defined.* The proposed implementation model would follow the local and global baseline address allocation policies defined by IANA and the RIRs. Thus, it adheres to the three primary goals of the Internet address distribution function namely Aggregation, Conservation, and Registration as defined by RFC2050 (1996).

Though the Internet architecture is designed for decentralized control and self-organization, the reasons for the RIRs to act as monopolies are partly technical and historical. In IPv4, due to early mistakes such as legacy IP address allocations and the limitation of the Internet and address architecture, there were certain constraints preventing further decentralization of the address distribution function. Maybe with today’s technology, with proper development of the address allocation scheme such as the *Expansionary Approach* defined in this thesis, could allow multiple organizations to compete cooperatively with each other in giving out IPv6 addresses to the users.

Though further decentralization of IPv6 address distribution is a challenge, it is an opportunity. This thesis believes that the IPv6 address-distribution function, managed as a single hierarchy, cannot be a dichotomy of either take it or leave it. Introducing further decentralization would remove monopoly and hence the users have an option to choose among suppliers. The peer Internet Registries (IR) can be more competitive (through coordinated competition) thereby promoting innovation, information sharing and enhance user's satisfaction. Further, it would help the IP address provider to avoid oversight if any, to be more responsive to user needs, to be more efficient in terms of operations, and to reduce bureaucratic overhead in terms of load and cost. This would benefit the users and the Internet community at large. The Expansionary Approach, if implemented, will accomplish one of the key purposes of ICANN that is *to allow for the development of robust competition in the management of Internet names and addresses* (NTIA, 1998).

1.3 Objective

The aim of this thesis is to define a method *to further decentralize the Next Generation IPv6 Internet Address distribution function*.

The main objective of this thesis is *to demonstrate that further decentralization for the allocation of Next Generation IPv6 Internet Addresses is possible without affecting the scalability and stability of the Internet routing system*.

1.4 Methodology

To accomplish the objective stated in the previous section the methodical research process detailed below is undertaken.

i) To provide a general discussion on Internet addressing and routing architecture; to further analyze the early Internet model to study and identify open issues, limitations, challenges; and to understand the requirements and the implications regarding centralization and decentralization of the address distribution function

ii) To survey the state-of-the-art of the Internet address distribution function and to study its merits and shortcomings. In addition, to analyze the implications of various address allocation algorithms for Internet routing.

iii) To perform a methodical and critical study on Internet routing and stability and to evaluate how the evolution of the Internet and user requirements have influenced Internet routing, stability and scalability.

iv) To define an appropriate IPv6 address space management process and a allocation framework on the Expansionary Approach for the allocation and distribution of IPv6 addresses based on the lessons learnt from section ii) and iii) above.

v) To define a hybrid address allocation algorithm that can handle fragmentation efficiently in the likely event there is a rapid and unprecedented growth of IPv6.

vi) To carry out decentralization by introducing alternative peer entities to the existing RIRs, for the allocation of IPv6 addresses. Then, to demonstrate mathematically and by simulation that further decentralization made possible through the Expansionary Approach, by the introduction of itself, will not add to or multiply or drastically increase the number of address prefixes to the Internet core routing table. The existing sparse and the proposed hybrid address allocation algorithm are used for this purpose.

vii) To define and detail an example implementation of the “Expansionary Approach for the allocation and distribution of IPv6 addresses” called the Community Internet Registry (CIR) model based on the principles of iv) and v).

1.5 Scope and Limitations

The Expansionary Approach defined in this thesis is one possible approach for further decentralization of IPv6 address allocation without affecting the scalability and stability of the Internet. Other approaches might be possible that is beyond the scope of this thesis. Further, the Community Internet Registry (CIR) model defined in this thesis is one example implementation of the Expansionary Approach while multiple instances are possible.

Though IPv6 solves the address scalability problem, it does not solve the routing scalability problem. As such, Internet routing scalability is still a concern. The Expansionary Approach defined in this thesis is not a solution to the existing Internet routing scalability concerns. However, the Expansionary Approach by itself does not add to or lead to address framentation.

The hybrid address allocation algorithm defined in this thesis uses Pareto principle to define growth rate and identify fast or slow users for simulation purposes and analysis. Apart from Pareto, other methods could be possible to define growth rate of user’s that is beyond the scope of this thesis. The Global Common Address Registry (GCAR) used in the proposed IPv6 address-space management scheme has a limitation. As all the RIRs and the Peer Entity will use the GCAR, there could be possible contentions when multiple user’s access it at the same time.

1.6 Contribution

The contribution of this thesis is summarized as follows.

i) A *hybrid IPv6 address allocation algorithm* that is a viable and efficient improvement over the existing sparse address allocation algorithm in minimizing fragmentation. The Expansionary Approach would use this hybrid address allocation algorithm that is futuristic in thought, to cover the potential growth of the Internet in the event it happens. The hybrid IPv6 address allocation algorithm leverages on the strengths of the existing address allocation algorithms namely, sparse, rate sparse, and the Growth-based Address Partitioning (GAP) algorithm. The proposed hybrid IPv6 address allocation algorithm will help to allocate addresses contiguously to a greater extent possible than would the state of the art solutions. The resulting improvement in address conservation and aggregation would lead to better and more sustainable routing scalability and stability.

ii) An *Expansionary Approach* for the allocation of IPv6 addresses. This allows for further decentralization of the IPv6 address allocation function without address fragmentation so that Internet Scalability or Stability is not affected. This increased decentralization would remove the current monopoly of the existing RIRs and allow peer Internet Registries (IR) to be more responsive, competitive, and innovative thereby benefiting the users.

iii) Define *one implementation model* of the 'Expansionary Approach' called the *Community Internet Registry (CIR) Model.* (Multiple instances are possible.)

1.7 Thesis Outline

This thesis is organized into six Chapters. Chapter 1 identifies the purpose of the thesis and introduces the problem statement, research objectives, and contributions of the thesis.

Chapter 2 reviews the Internet architecture in terms of the current IP address allocation algorithms, Internet routing scalability and stability, implications of Internet core routing table growth, and related work.

Chapter 3, the core chapter of this thesis, introduces the frame work and architectural design of the ‘Expansionary Approach for the allocation of IPv6 addresses’.

Chapter 4 presents the mathematical verification and the simulation experiments to validate the proposed ‘Expansionary Approach’, and includes the analysis and discussion made on the result obtained.

Chapter 5 presents one example implementation of the Expansionary Approach for the allocation of IPv6 addresses called the ‘Community Internet Registry’ (CIR) model.

Chapter 6 summarizes the thesis with a conclusion and suggestions for future work.

CHAPTER 2
A REVIEW ON THE INTERNET ADDRESS ALLOCATION, ROUTING SCALABILITY AND STABILITY

Those who do not learn from history are doomed to repeat it.

\- George Santayana

This chapter sketches an overview of the Internet architecture in terms of addressing and routing. This understanding helps to evaluate the limitations of the present Internet address and routing architecture that follows a topological hierarchy in handling scaling pressures. By this the inadequacy and the implications of the various address allocation algorithms are identified. The cause, effect, the lesson learned, and implications of the rapid growth of the routing tables in the Default Free Zone (DFZ), on Inter-domain routing and stability are identified.

This chapter also provides a background against which the proposed 'Expansionary Approach' that could facilitate further decentralization for allocation of the Next Generation IPv6 Internet addresses can be contrasted.

2.1 An Overview of Internet Addressing

The *Internet* is a collection of interconnected computer networks. These Network's use the standard *Internet Protocol Suite* (Transmission Control Protocol/Internet Protocol, TCP/IP) to communicate with each other. TCP/IP, named after its two prominent protocols TCP (RFC793, 1981) and IP (RFC791, 1981), is a model architecture that conceptually divides the network into a set of layers and protocols (RFC1122, 1989; RFC1123, 1989). The Internet Protocol was to handle addressing while, TCP was to handle transport and make it reliable. The *Internet*

Protocol is a set of rules and procedures that provides for transmitting blocks of data called datagram's from sources to destinations where source and destination are hosts identified by fixed length IP addresses (Clark, 1988; RFC760, 1980). A host is a computer connected to the Internet.

The set of layers, protocols and standards defines the Internet architecture. In the context of the Internet architecture, addresses are used for several different functions. The 'name' of a resource indicates what we seek, an 'address' indicates where it is, and a 'route' tells us how to get there (IEN19 1978; IEN23 1978). IP addresses are a finite resource and their careful management is essential to the running of the Internet (Roberts and Challinor, 2000). IP addresses and addressing issues are basic elements of routing. Currently, there are two types of addresses in active use, IPv4 and IPv6. An understanding of the history and fundamentals of IP addressing will help to grasp quickly the Internet routing concepts and its scaling problems. For brevity, the evolution of the Internet and Internet addressing, and the associated Internet scalability problems are given in Appendix A.

2.2 Internet Address Distribution

2.2.1 Structure

Internet addresses namely, IPv4 and IPv6 are allocated on a regional basis in a delegated fashion to avoid fragmentation. IANA with its role dating back to 1970's is responsible for the global coordination of the DNS root, IP addresses and AS numbers, and other protocol resources (IANA, 2010b). Since 1998, operated by ICANN, a not-for-profit internationally-organized entity set up by the global community as the steward for the IANA functions (Davies, 2008). In RFC1881 (1995), the IETF recognized IANA as the central authority on the management and allocation of IPv6 address space for the