IPv4 - How long have we got?

August 2003

Geoff Huston

An Invitation to the Reader

This article describes the outcomes of a predictive exercise looking at the potential usage rates of IPv4 address space in the coming years. As with any predictive exercise, the conclusions drawn in this work are not certain, and other analyses of the data may produce different outcomes. There is also consideration that the introduction of new technologies, different forms of use of a ubiquitous IP network, or some other explosive expansion of the network will have an impact on these projections.

The article also includes an interpretation of the historical allocation data as being an outcome of effective implementation of the Regional Internet Registries' address distribution policies and functions. These policies are determined by a consensus-based process within regional open policy forums, and changes to these policies may be adopted by consensus within these forums. Changes in these policies may effect address consumption rates. It is also noted that Address distribution functions have commercial and social implications as well as technical outcomes, and the article makes some value judgments related to these policies based on technical grounds without looking in detail at other forms of outcomes of the address distribution function.

There are other many other views on these topics. To look at this diversity of perspective, I would like to readers of this article to send me any comments that arise after reading this article. You may be aware of other studies or reports on address space consumption, or other perspectives on the address distribution operation and its outcomes. If there is sufficient response by October 2003, I'd like to include such comments and perspectives in a followup column that looks at address distribution functions from this broader perspective. So if you have a view on this topic of address consumption and distribution functions, please type it up and send it to me at gih@telstra.net.

Geoff Huston
July 2003

Predicting the future is easy. The hard bit is always getting it right.

Obviously there are a limitless ways to look into the future and make some pronouncement. In terms of professional occupations it's up there with a few others as a candidate for being the oldest one in the books. Whether it's consulting the flight of birds in the sky or performing feats of mathematical manipulation on a series of measurements of stock prices, or simply making wild-eyed guesses, there's no end of the various ways we've come up with to guess at the unknowable.

One of the more fascinating methods of divination, and one of the oldest recorded forms of writing, can be seen in the National Palace Museum in the city of Taipei, where a collection of Oracle Bones is on display. In this very ancient Chinese method of divination the questions would be engraved on the surface of a shell or bone fragment, and surrounding it would be a number of potential answers. On the reverse side of the bone an indentation would be drilled into the shell. The shell would then be placed over heat. The indentation forms a stress point in the bone, and the heat causes the bone to crack outward from the indentation with a sharp snapping sound. The sound of the snap, and the length, direction and strength of the crack would form the basis of the divination.

These days we've managed to replace the bone with a spreadsheet. While it's often a lot faster, it's far less dramatic as a piece of theatre, and it's always questionable whether the accuracy of the divination has improved any case.

In this article I'd like to revisit a particular piece of analysis that has been a topic of considerable interest at various times over the past decade or more. The basic question is "how long can the IPv4 address pool last in the face of a continually growing network?" We've seen in the industry press at regular intervals dire reports that the IPv4 sky is falling and somewhere on the globe they've '"run out" of addresses. Once again it's probably time to take a more considered look at the problem and see what numbers come out from this exercise using data collected up to 2003.

The IPv4 address space

The initial design of IPv4 was extremely radical for it's time in the late 1970's. Other contemporary vendor-based computer networking protocols were designed within the constraints of minimizing the packet header overhead in order to cram the maximal amount of data into the relatively sparse network bandwidths of the time, and address spans were defined within the overall assumption that the networks were deployed as islands of mainframe-based connectivity. In many protocol designs 16 bit's of address space in the packet header was considered an extravagance, particularly so since in many cases the vendor hadn't even sold anywhere near 2 to the 16th power of numbers of computers. To dream of a multitude of computers, each attached to a single global network was a very far fetched dream, and then to use a globally unique address framework of 32 bit's to number them was truly outlandish. After all, 2 to the power of 32 is just under 4.5 billion, and at the time this was somewhere around ten to twenty times the number of telephone handsets in the world. Someone was possibly making some very grand assumptions indeed about the future of the Internet!

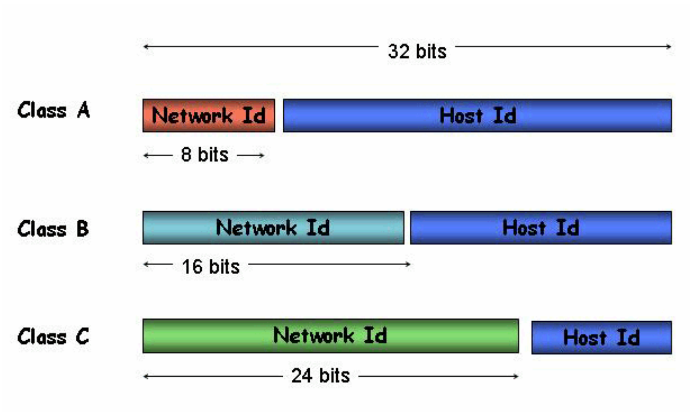
To further add to the radical nature of the exercise, the Internet Network Information Center was prepared to hand out unique chunks of this address space to anyone that wanted it. Address deployment architectures in contemporary protocols did not have the address space to support such extravagance, nor did they even see a need for global uniqueness of addresses, so everyone numbered their isolated networks starting at the equivalent of '1', and progressed from there. When corporate mergers forced a network merger it was invariably time for a network consultant's feeding frenzy as both networks required complete redesign. Whereas, it seemed, the Internet address architecture was pre-built for inter-connection. It was as if it was the phone system being constructed from the outside in.

I have heard recollections from one of those involved with the 32 bit design decision that some folk thought that even this decision was too conservative. It was reported that consideration was given to a variably sized address field in the packet header, allowing the address space to expand even further over time. The countervailing view was evidently that variable-size fields in packets require greater number of cycles in the forwarding engines to process this packet, and this was a needless overhead.

IPv4 Address Architectures

IP uses the address to express two aspects of a connected device: the identity of this particular device (endpoint identity) and the location within the network where this device can be reached (location or forwarding identity). The original IP address architecture used the end point identity to allow devices to refer to each other in end-to-end application transaction, but within the network itself, it used a sub-field of the address to undertake forwarding. The architectural assumption behind this scheme was that all devices that shared a common network sub-field were grouped together, and could pass packets between each other without required any form of IP network forwarding.

The resultant network architecture had two fields; a network identifier and a host identifier within that network. The first incarnation of this architecture used a division at the first octet: the first 8 bit's were the network number, and the following 24 bit's were the host identifier. The underlying assumption was deployment across a small number of very large networks. This view was subsequently refined, and the concept of a Class-based address architecture was devised. One half of the address space was left as a 8/24 bit structure, called the Class A space. This allowed for up to 127 networks each with 16,777,216 host identities. One quarter of the remaining space used a 16/16 bit split, allowing for up to 16,128 networks, each with up to 65,536 hosts, the Class B space. A further one eighth of the remaining space was divided using a 24/8 bit structure, allowing for 2,031,616 networks, each with up to 256 hosts, the Class C space. The remaining one eighth of the space was held in reserve.



This address scheme was devised in the early 1980's, and within a decade it was pretty clear that there was a problem. It was running out! The reason was an evident run on Class B addresses. While very few entities could see their IP network spanning millions of computers, the personal desktop computer was now a well established part of the landscape, and networks of just 256 hosts were just too small. So if the Class A space was too big, and the Class C too small, then Class B was just right!

Well not exactly "just right". More accurately, "the best of a bad choice". The Class B blocks were also too large, and most networks that used a Class B address consumed only a few hundred of the 65,535 host identities within the Class B network. The addressing efficiency of this arrangement was very low, and a large amount of address space being consumed to number a small set of devices. Achieving even a 1% host density was better than normal, and 10% was considered pretty exceptional.

Consequently, Class B networks were being assigned to networks at an exponentially increasing rate. Projections from the early 1990's forecast exhaustion of the Class B space by the mid-1990's. Obviously there was a problem here of relatively immediate proportion and the Internet Engineering Task Force (IETF) took on the task of finding some solutions. There were a number of responses devised by the IETF. As a means of mitigation of the immediate problem the IETF altered the concept of a network identifier. Rather than being a Class-ful fixed length identifier of either 8, 16 or 24 bit's in size, the network identifier would be any length at all, and a network identifier was now the couplet of an IP address prefix and the bit length of the network part. The boundary between the network and host part could change across the network, so rather than having 'networks' and 'sub-networks' as in the Class-based address architecture, there was the concept of a variable length network mask. This was termed the "Classless" address architecture, and the step was considered to be a short term expediency to buy some additional time. The longer term plan was to develop a new IP architecture that could encompass a much larger connectivity domain than was possible with IPv4.

Well, we now have IPv6 as the longer term outcome. But what has happened to the short term expediency of the Classless address architectures in IPv4? It appears to have worked very well indeed so far, and now the question is how long can this short-term solution last?

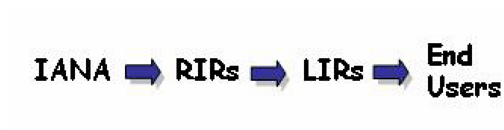
Predictions

Predicting the point of IPv4 address exhaustion has happened from time to time since the early 1990s within the IETF. The initial outcomes were clearly visible by the mid-1990's: the Classless address architecture was very effective in improving the address utilization efficiency, and the pressures of ever-increasing consumption of a visibly finite address resource were alleviated. But we're well beyond that time now. One boom later it's a big Internet out there, and it's probably good to understand where we are heading with the underlying network address pool.

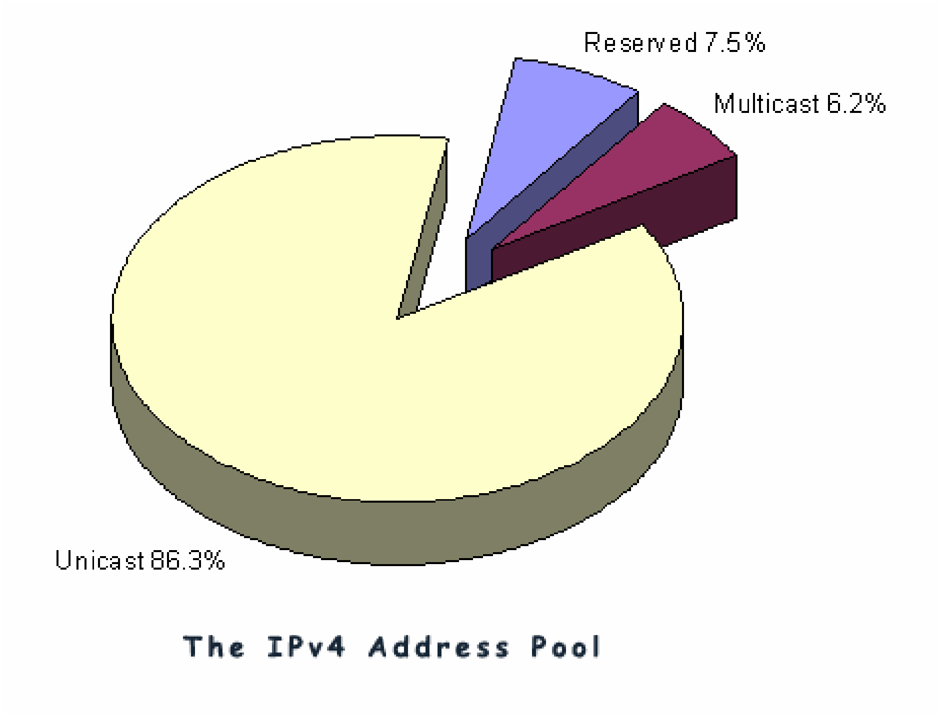
So lets prepare an Oracle Bone, scribe up the question, and light to the fire to see what the IPv4 address future looks like.

IP Addresses

There are three stages in address allocation. The pool of IP addresses is managed by the Internet Assigned Numbers Authority, IANA. Blocks of addresses are allocated to Regional Internet Registries, who in turn allocate smaller blocks to Local Internet Registries (LIR's) or Internet Service Providers (ISP's).



Currently there are 3,707,764,736 addresses that are managed in this way. It is probably easier to look at this in terms of the number of "blocks" where each block is the same size as the old Class A network, namely 16,777,216 addresses. The total address pool is 221 /8 s, with a further 16 /8's reserved for Multicast use, 16 /8's held in reserve, and 3 /8's are designated as not for use in the public Internet. So the way the address space as been divided up is shown in the following pie chart.



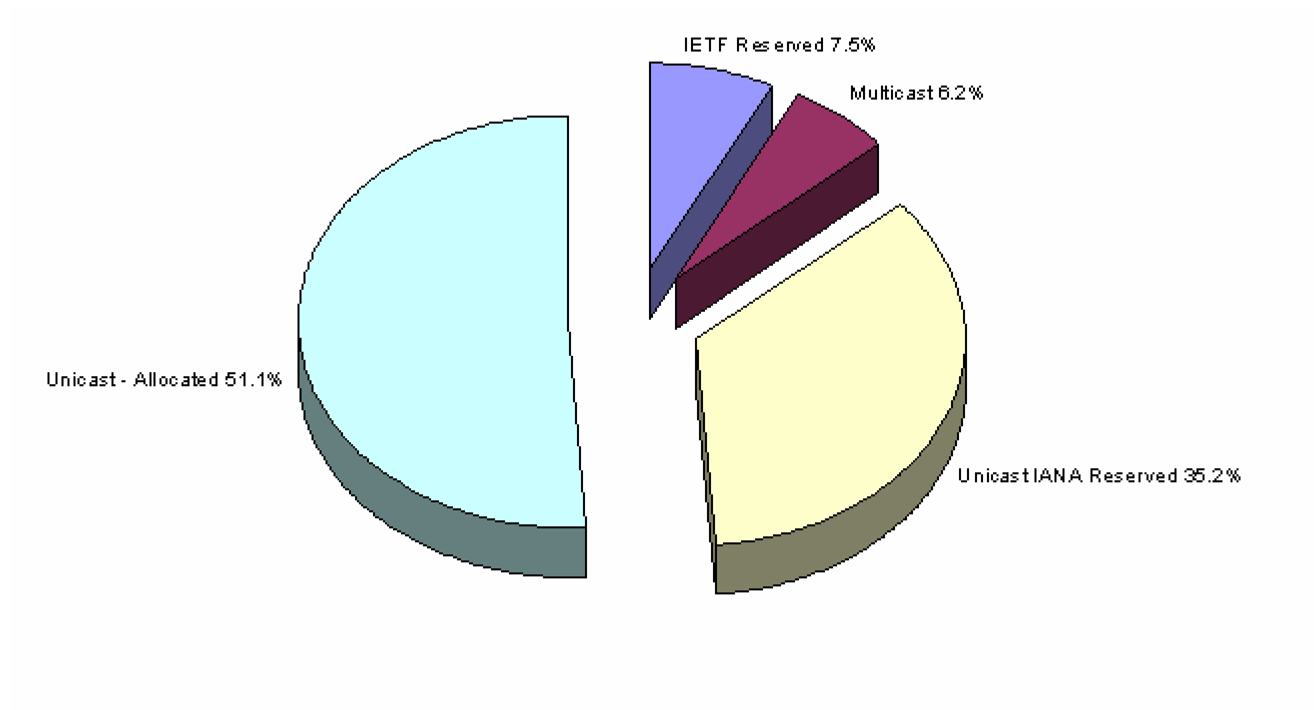
In looking at futures there are three places to look for data:

- how quickly is the IANA passing address blocks to the RIR's, and when will IANA run out?
- how quickly are the RIR's passing address blocks to LIRs, and when will this run out?
- how much address space is actually used in the global Internet, and how quickly is this growing? When will this run out?

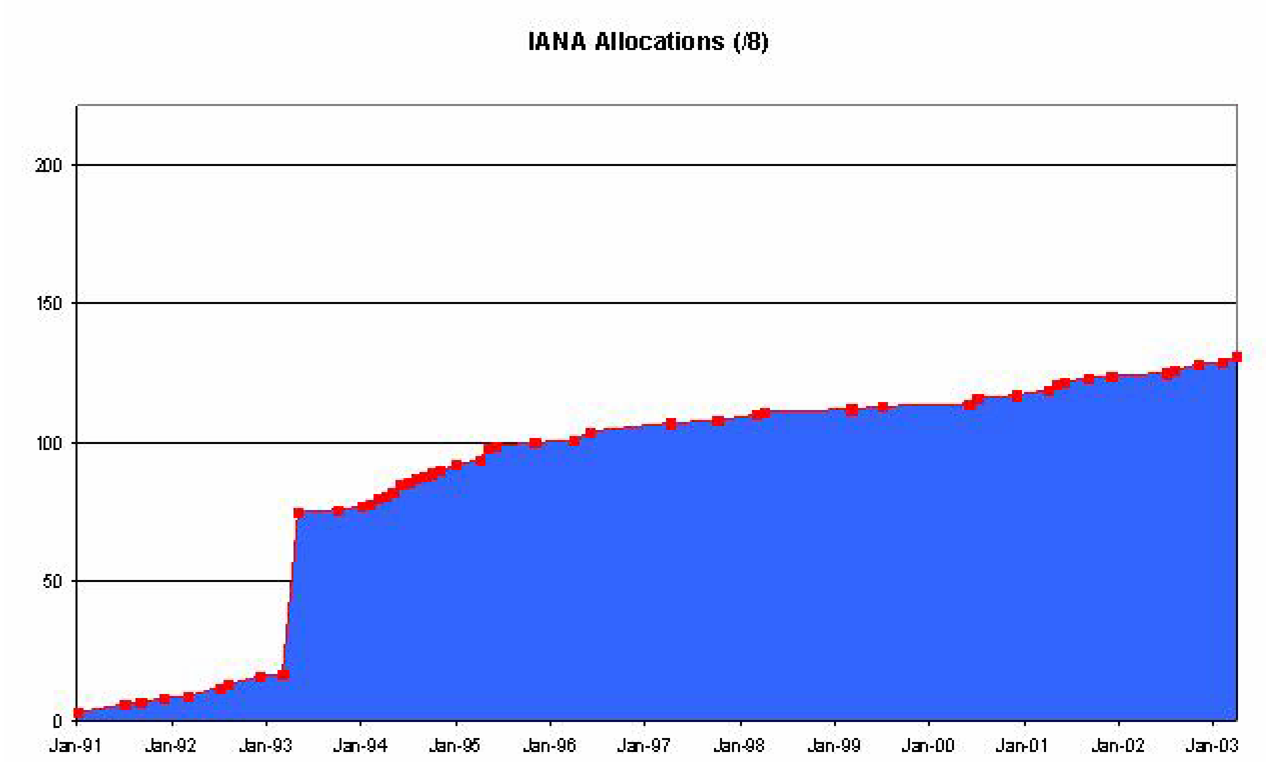
The IANA Registry

So the first place to look is the IANA registry file. Perhaps the most striking aspect of this record is that there is nothing older than 1991! This exposes one of the problems with analyzing such data, in that there is a difference between the current status of a registry, and a time-stamped log of the transactions that were made to the registry over time. The data published by the IANA is somewhere between the two, but the log data is incomplete and the current status of some address blocks is very unclear.

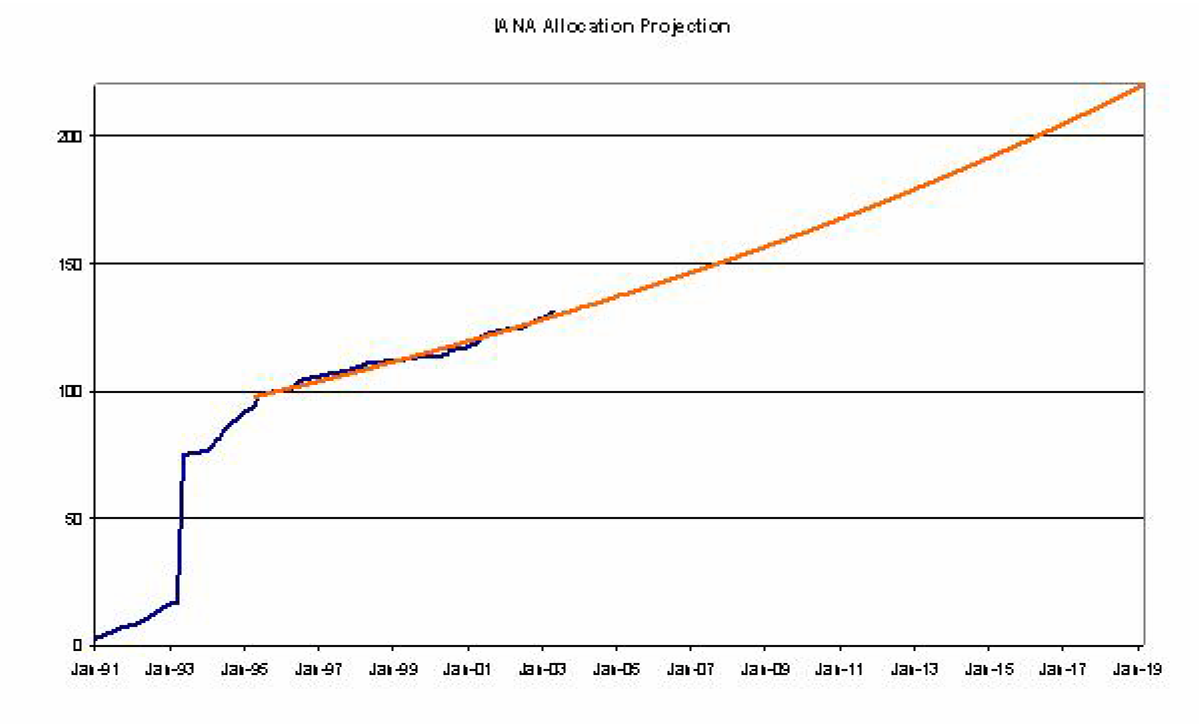
The registry reveals that of the 221 /8 blocks 90 are still held as unallocated by the IANA, and the remaining 131 have already been allocated in various ways.



The IANA registry also includes the date of allocation of the address block, so it's possible to construct a time series of IANA allocations.



The data relating to allocations prior to 1995 looks like it's not the actual date of allocation (as IANA allocations were performed through the 1980's), so it appears that the useable data starts in 1995. So if we take the data starting from 1995 and perform a linear regression to find a best fit of an exponential projection, it's possible to make some predictions as to the time it will take to exhaust the remaining 50 /8's. (Assuming of course that the underlying and consistent model of growth is one where the expansion of the network is proportional to it's size, rather than being a constant growth factor.)



The projection of 2019 is perhaps surprising, as it seems that the network is bigger now than ever, yet the amount of additional address space required to fuel further accelerating growth for more than a decade is comparatively small.

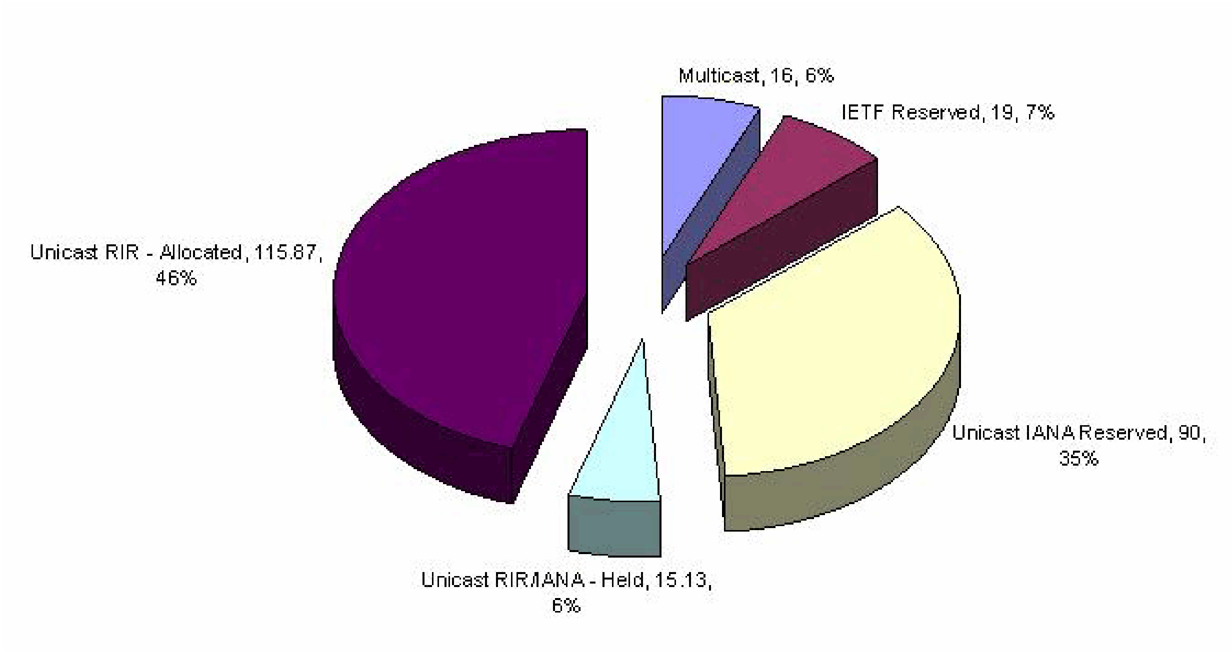
There are perhaps three reasons why this is the case, and the turning point when these aspects gained traction in the Internet appeared to be around 1995.

- The first 1.6 billion addresses (equivalent to some 100 /8 blocks) were allocated using the Class-based address architecture. Since this date address allocation has used a Classless architecture, and this has allowed for significantly improved efficiencies to be achieved in using the address space.
- The Regional Internet Registries (RIR's) came into the picture, and started using conservation-based policies in address allocations. The RIR process requires each address applicant to demonstrate that they can make efficient and effective use of the address space, and this has dampened some of the wilder sets of expectations about an enterprises' address requirements.
- Address Compression technologies became widely deployed. Dynamic Network Address Translation devices (NATs) have, for better or worse, become a common part of the network landscape. NATs allow large 'semi-private' networks to use a very small pool of public addresses as the external view of the network, while using private address space within the network. Dynamic Host Configuration Protocol (DHCP) has allowed networks to recycle a smaller pool of addresses across a larger set of intermittently-connected devices.

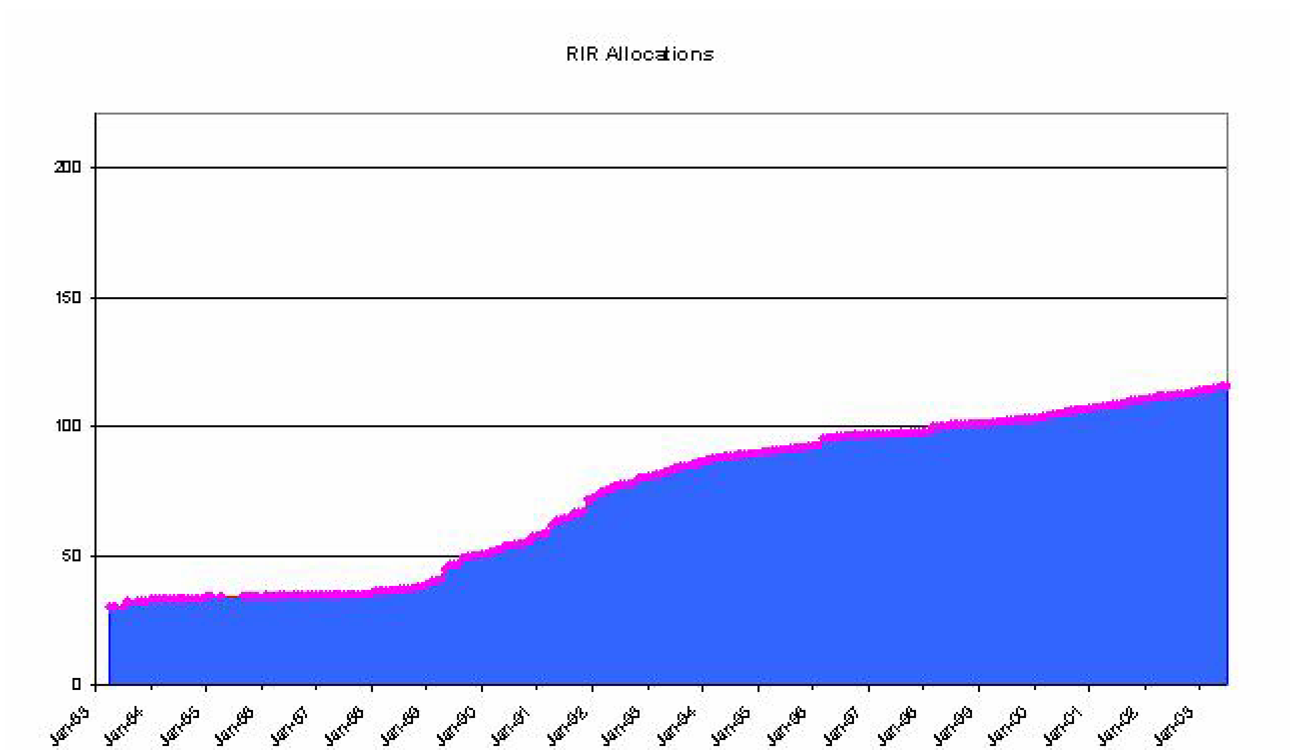
Will these factors continue to operate in the same fashion in the future? Will future growth in the use of public address space operate from a basis of a steadily increasing accelerated growth? Of course there are some real weaknesses in the assumptions behind this form of extrapolation, and we'll look at some of these in further detail later. The assumptions made in this exercise are that it depends on the continuity of effectiveness of the RIR policies and their application, continuity of technology approaches and the absence of any disruptive triggers. While the RIR's have a very well regarded track record in terms of application of a policy of fair conservation of the address resource, and there are strong grounds for confidence that this will continue, obviously the latter two assumptions about technology and disruptive events are not all that comfortable. With that in mind the next step is to look at the RIR assignment data.

The RIR registries

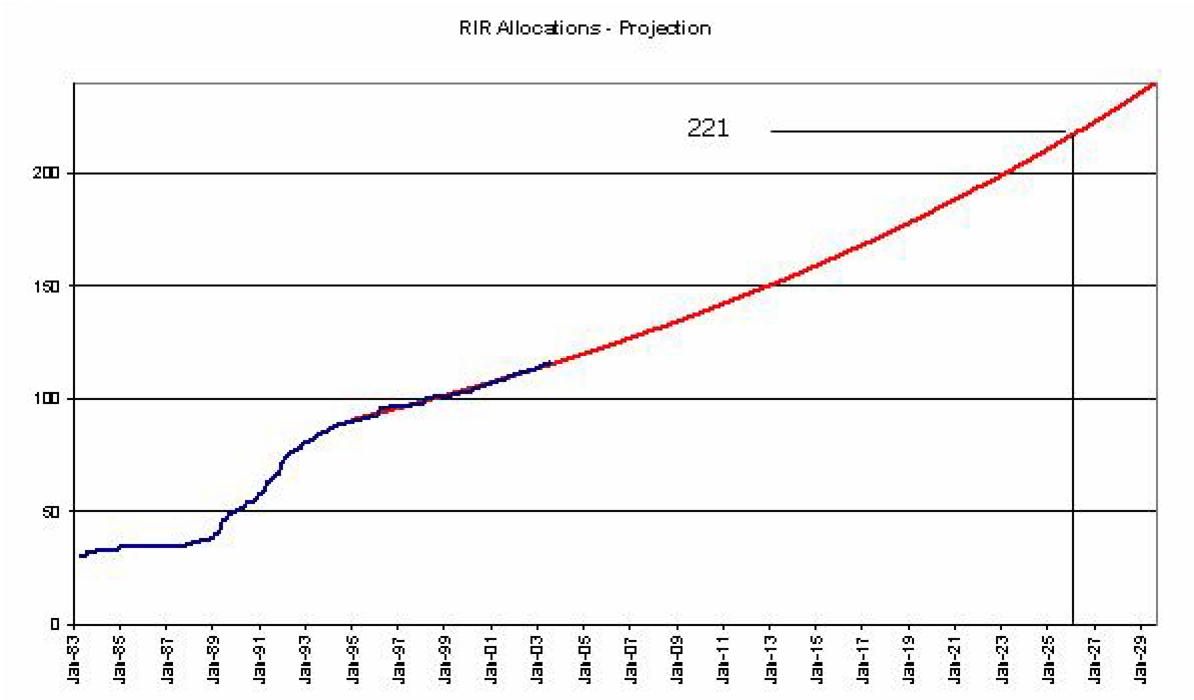
The RIR's also publish a registry of their transactions in "stats" files. For each currently allocated or assigned address block the RIR's have recorded, among other items, the date of the transaction that assigned an address block to a LIR or ISP. Using this data we can break up the 131 /8 blocks further, and it's evident that the equivalent of 116 /8 blocks have been allocated or assigned by the RIR's, and the remaining space, where there is no RIR allocation or assignment record is the equivalent of 15 /8 blocks



These transactions can again be placed in a time series, as shown below.



The post-1995 data used to extrapolate forward using the same linear regression technique described above, to find a curve of best bit using the same underlying growth model assumptions:



This form of extrapolation gives a date of 2026 for the time at which the RIR's will exhaust the number pool. If the withheld 16 /8's are bought into play, 2029 would be predicted by this approach.

Again the same caveats about the weakness of this approach as a reliable predictor apply here, and the view forward is based on the absence of large scale disruptions, or some externally-induced change in the underlying growth models for address demand.

The BGP Routing Table

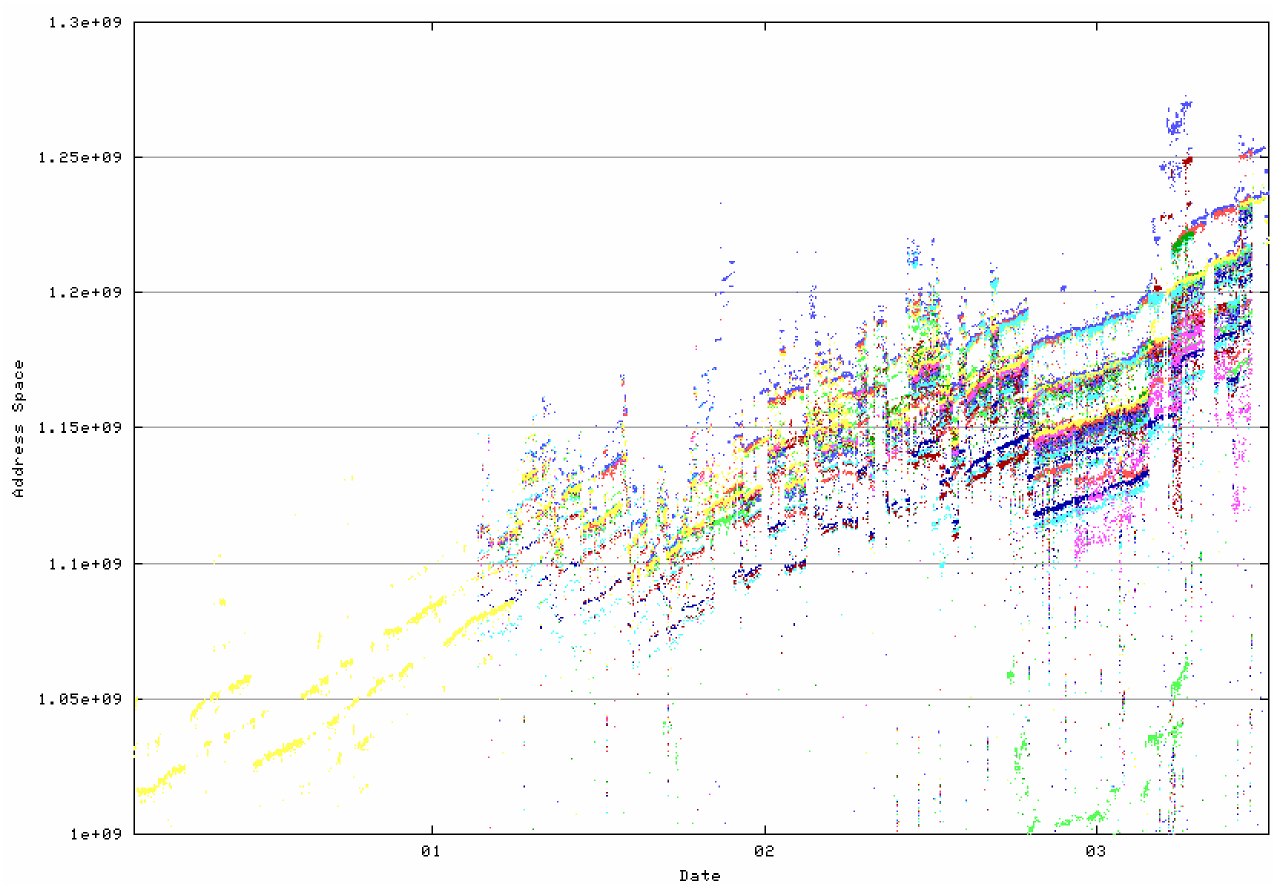
Once addresses are assigned to end networks, the expectation is that these addresses will be announced to the network in the form of routing advertisements. So some proportion of these addresses are announced in the Internet's routing table. How large is the address space covered by the routing table?

There is a rather unique router operated within the campus of the University of Oregon (www.route-views.org). This router does not actually route any packets at all, but instead operates with a very impressive set of inter-domain routing peers. Within the internal routing table of this box is the current view of the Internet's global routing table collected from all over the globe and all over the topology of the Internet.

Perhaps the best way to illustrate the unique power of this approach is to take an analogy using map construction. A single view of routing is like standing on a street corner and looking around you in every direction for as far as you can see, and trying to construct a map of the city. You'll get a large map of those avenues heading directly away from you, but the cross streets are hidden from your view. Maybe to get a more complete view you need to head to a number of different corners and do the same thing at each location. But what if the road net is constantly changing? What if, when you change locations you not only get a different perspective, but a different perspective of an altered underlying network? This would be very similar to the environment of dynamic routing, where changes, both large and small, are constantly being made to the network. Maybe the answer is to rise above it all and get a view from above. Unfortunately it is not possible to rise up over the network in the world of routing. So if we want to construct a richer map that shows more detail the next best thing is to get the relative view from a number of locations and construct the map from that. But as the world you are tying to map is constantly being altered, collecting these views at different times cannot generate a coherent map. So we need a number of views taken at the same time and assemble them into a larger picture.

The Route-Views project does precisely this, in real time. It collects a number of relative routing views simultaneously and assembles them into a combined view of the Internet. Coupled to this router is an archive of periodic snapshots of the assembled routing table. As a research tool for investigating changes in the characteristics of the Internet in terms of routing and addressing this is a highly valuable resource.

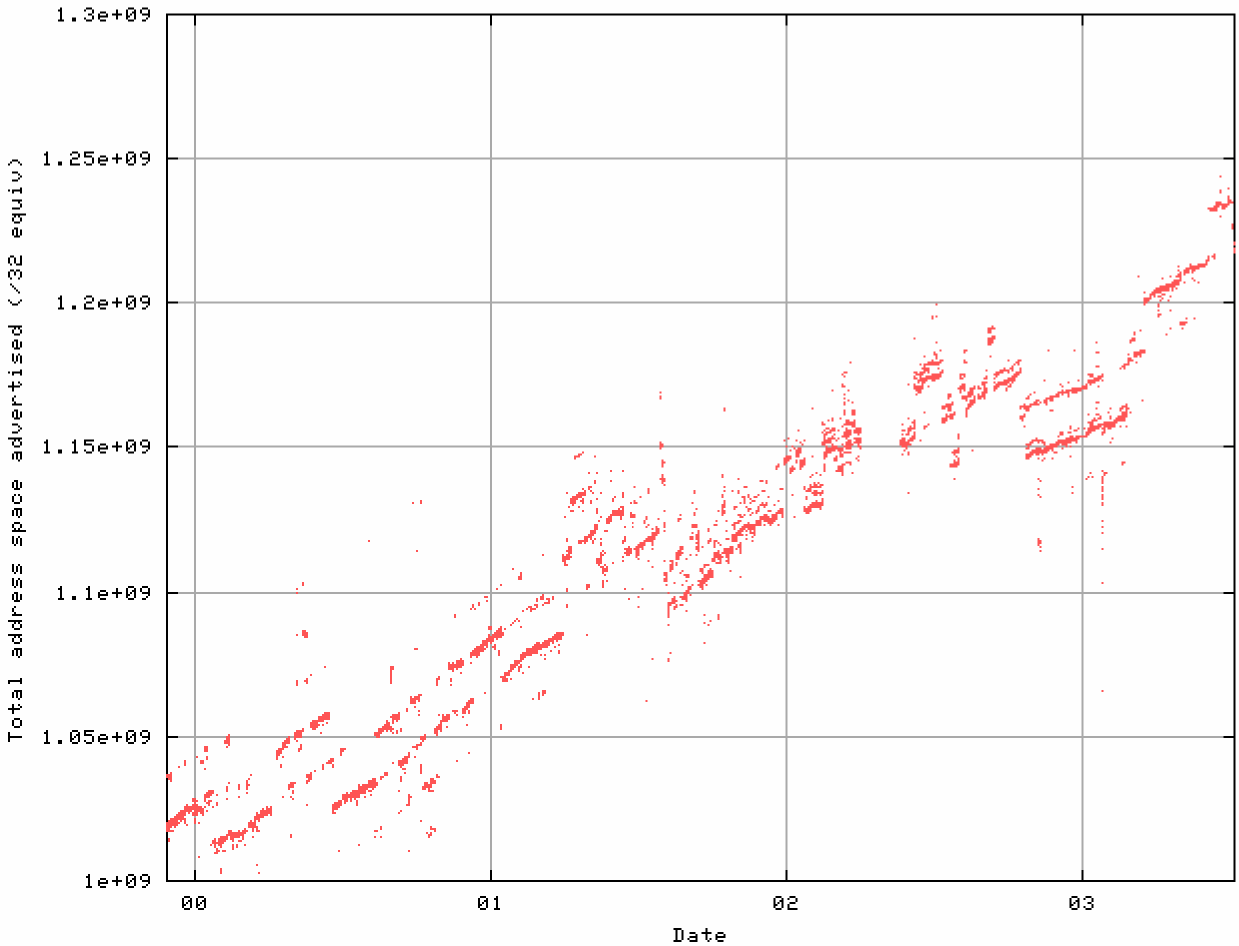
Analysis of the BGP routing table at the Route-Views router provides an interesting answer in terms of the amount of advertised address space:



Route-Views has over 30 inter-domain routing peers, and each peer sends it a complete set of advertisements. The figure shows the amount of address space spanned by each peer over time. The measurements are taken every 2 hours, and the data spans from February 2000 until the present.

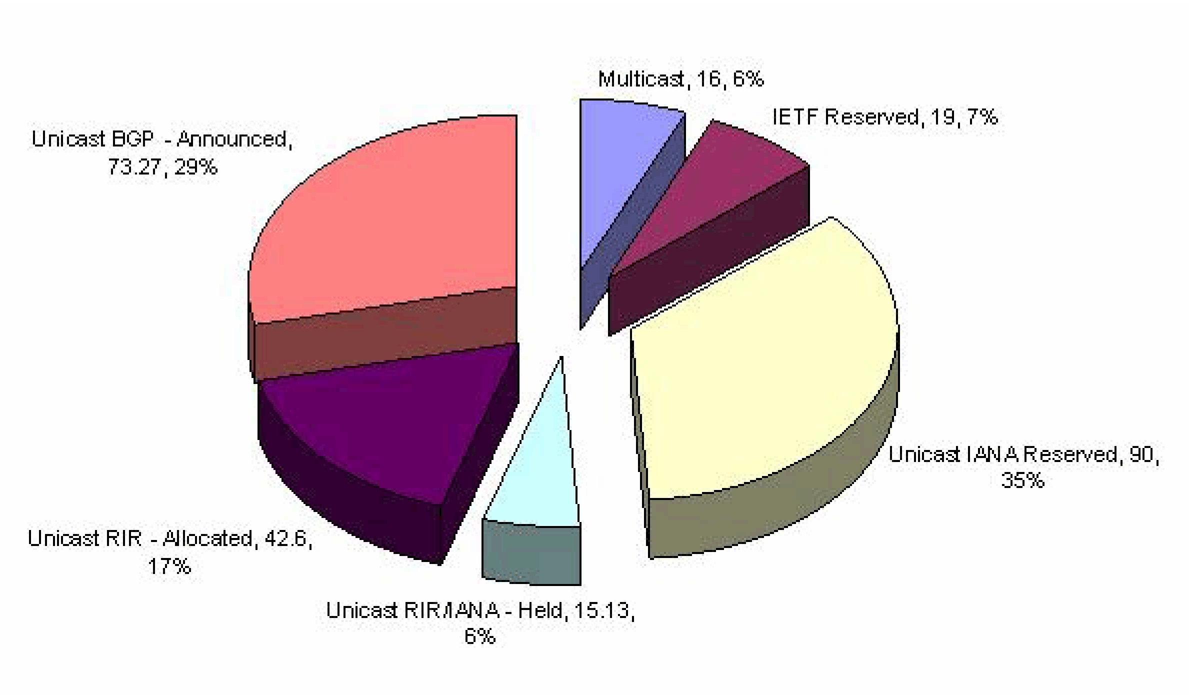
Oddly, to me at any rate, it's a very noisy graph. While all peers see a common subset of address space, each peer does not have the same view of the total span of the network. At any point in time the network is not 'completely connected' and various parts of the network are isolated from other parts. The second observation is the apparent 'layering' of the graph into a number of distinct bands. Each band is separated from it's neighbor by some 17 million addresses. That number is equivalent to a /8 address block, and it's evident that even very large address blocks are not stably announced in the Internet. There appears to be more churn in connectivity in the Internet than we would expect in looking at the base protocol behaviors.

This aggregated view of the Internet is challenging to distill into a single time series of data. An alternative approach is to take a single view of the address span of the Internet. This is the view from one point, inside the AS1221 network operated by Telstra:



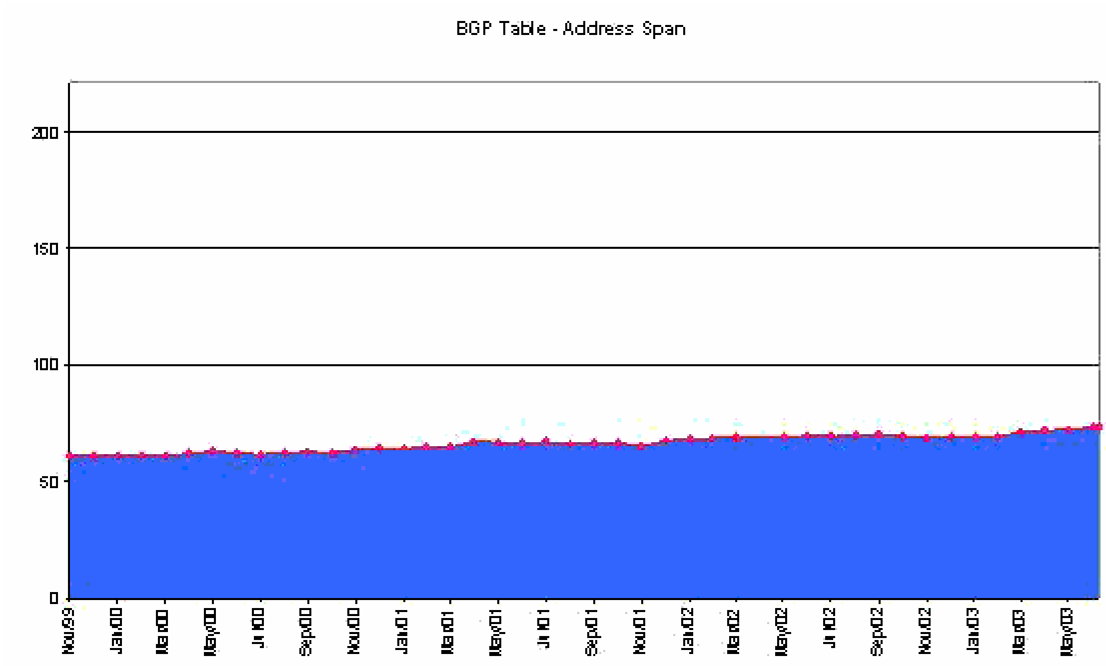
In terms of isolating a picture of address growth over time, it's a bit better, but there's still a lot of instability.

Using the most recent data from AS1221, we can now break up the allocated address space into "announced" and "unannounced" categories. This now reveals a clearer view of the complete disposition of the IPv4 address space

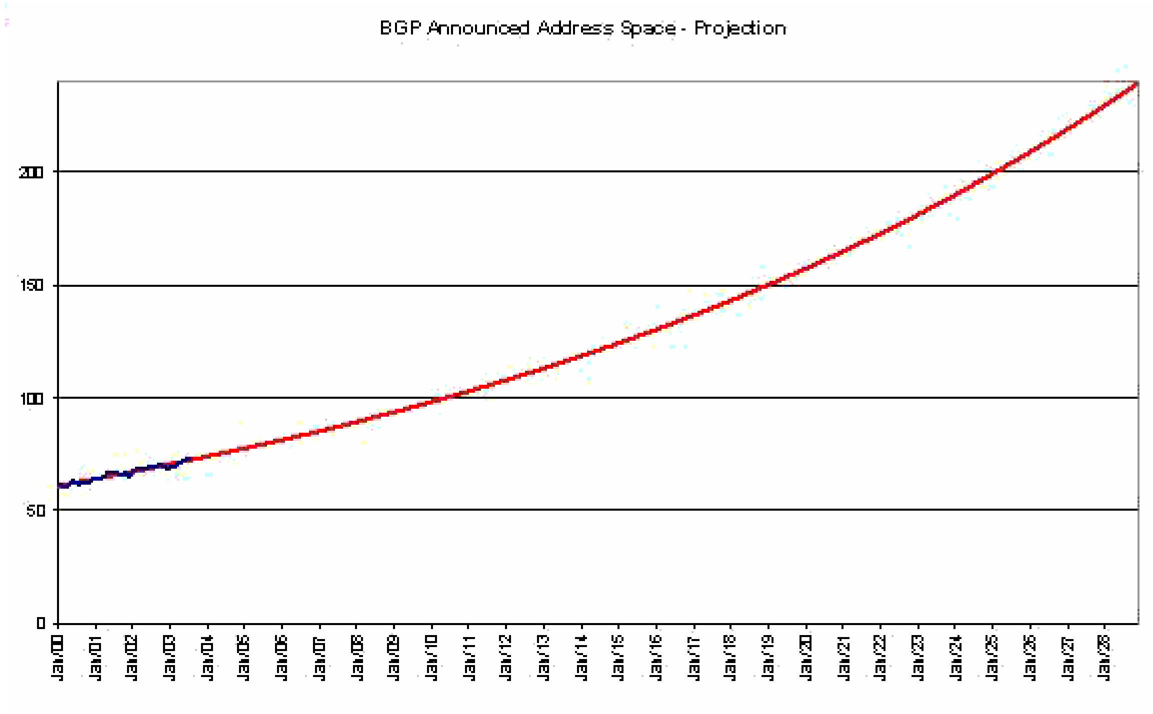


Some 29% of the space is announced in the BGP routing table, while 17% has been allocated to an end user or LIR but is not announced on the public Internet as being connected and reachable. 6% of the address space is held by the RIR's pending assignment or allocation (or at least there is no RIR recorded assignment of the space), while 35% of the total space remains in the IANA unallocated pool. A further 6% of the space is held in reserve by the IETF.

Returning to the view of total announced address space, as gathered from the perspective of AS1221, it is possible to plot a time series of the smoothed BGP data.



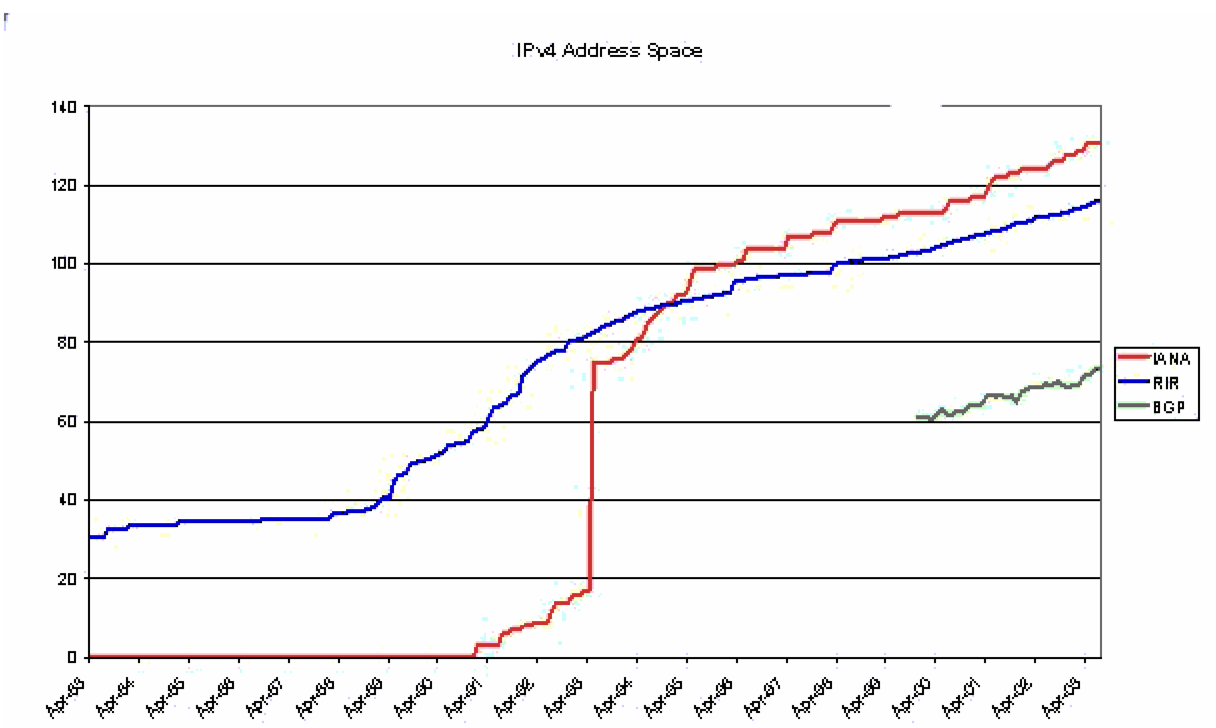
And, again using the same set of assumptions about the underlying growth model, where the growth in the total advertised address space is proportional to the size of the advertised address pool, extrapolate forward.



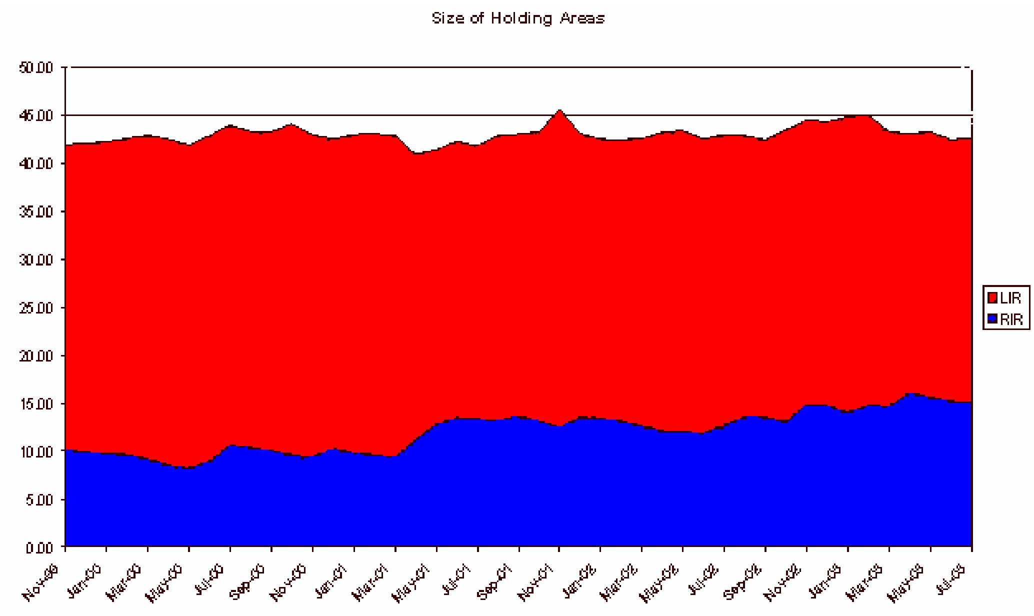
The outcome from this view, with a predicted address exhaustion date of around 2029, is slightly different to the RIR allocation prediction, but certainly consistent within the bounds of the relatively large level of uncertainty behind the assumptions being made to undertake the prediction.

Combining the Three Views

The data sets from IANA, the RIR's and the BGP table can be directly compared.

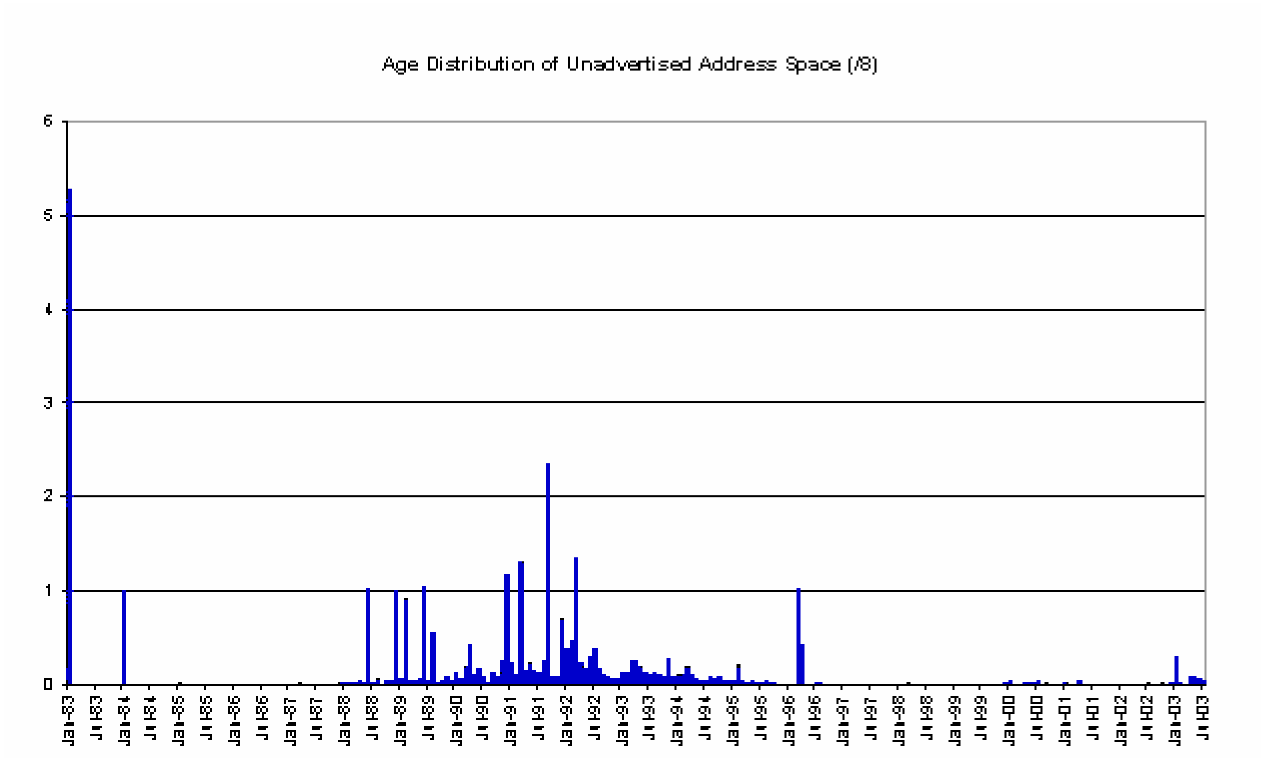


The range over which these three data sets can be directly compared is limited to the last three years. The next question is whether the three series are in step with each other, or whether there are different growth rates that are visible. One way to look at this is to look at the differences in the three series, which correspond to the amount of address space held by the RIR's pending future allocation or assignment and the amount of address space held by LIRs, ISPs or end users that is assigned but not announced

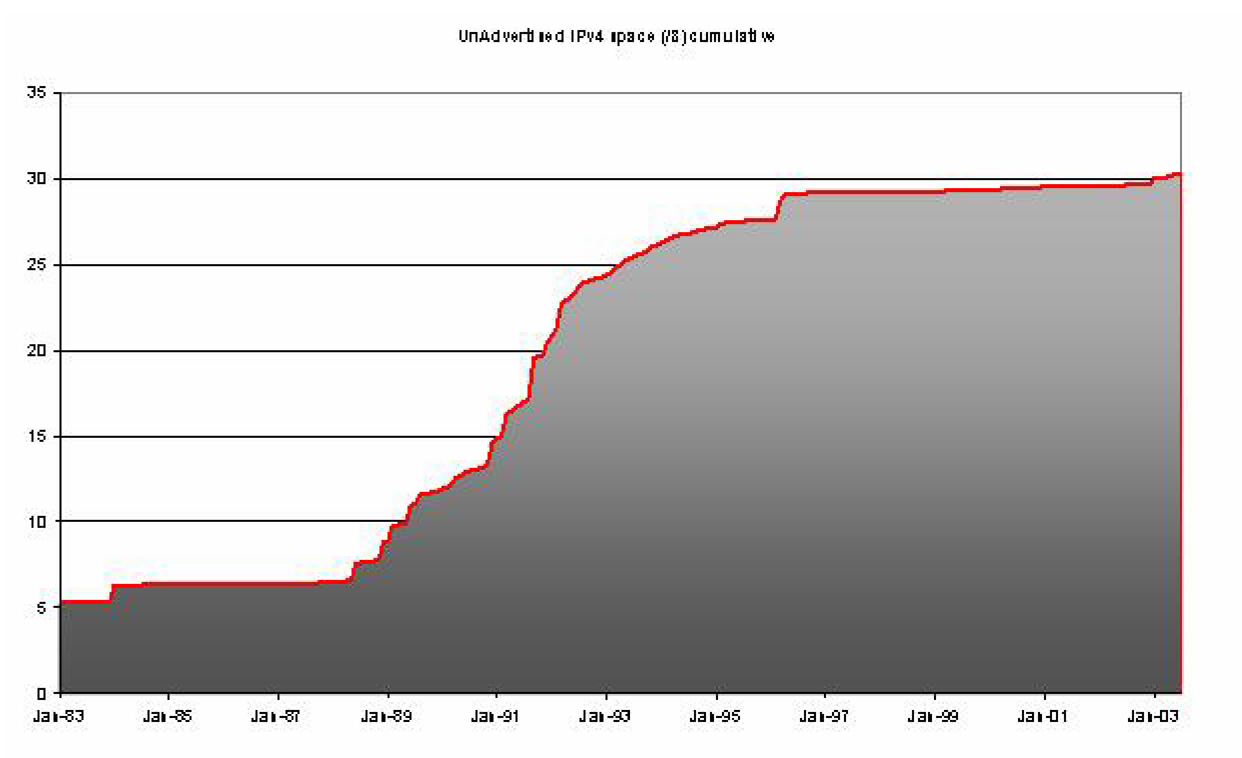


The LIR space of unannounced but allocated address space is a very large component of the total IPv4 address pool. It spans some 17% of the total address space, or the equivalent of 42 /8's. Is this a legacy of the address allocation policies in place before the RIR system came into operation in the mid 1990's, or some intrinsic inefficiency in the current system? If it's the latter, then it's likely that this pool of unannounced addresses will grow in direct proportion to the growth in the announced address space, while if it's the former then the pool will remain relatively constant in size in the future.

We can look back through the RIR allocation data and look at the allocation dates of unannounced address space. This view indicates that the bulk of the space is a legacy of earlier address allocation practices, and that since 1997, when the RIR operation was fully established, there is an almost complete mapping of RIR allocated address space to BGP routing announcements. (There is a set of allocations where no data is recorded for the assignment, and these appear to be the result of pre-1995 allocations. They are shown here with a date of January 1983.) The recent 2003 data indicates that there is some lag between recent allocations and BGP announcements, most probably due to the time lag between an LIR receiving an allocation and subsequent assignments to end users and advertisement in the routing table.



As this pool of addresses is large, its behavior over time is critical to the entire forward projection. So if we take a cumulative view of the size of this unadvertised address pool we can gain some view as to whether this pool is continuing to grow, and at what rate.



The slope of the growth of this unadvertised allocated address space in the period 1997 - 2002 is relatively small, so there is little growth in the unadvertised address space in recent time.

It is now possible to construct a model of the address distribution process, working backward from the BGP routing table address span using a number of assumptions:

1. The amount of RIR-allocated or assigned address space that remains unannounced in the BGP routing tables will increase slowly over time. The model used here is that of a slowly increasing percentage of the total announced space, plus a shorter term oscillation spanning 2 /8 blocks in size. The rationale for the slow increase in the LIR assignment inefficiency lies in consideration of the increasing costs of achieving high allocation efficiency as the size of the address pool increases

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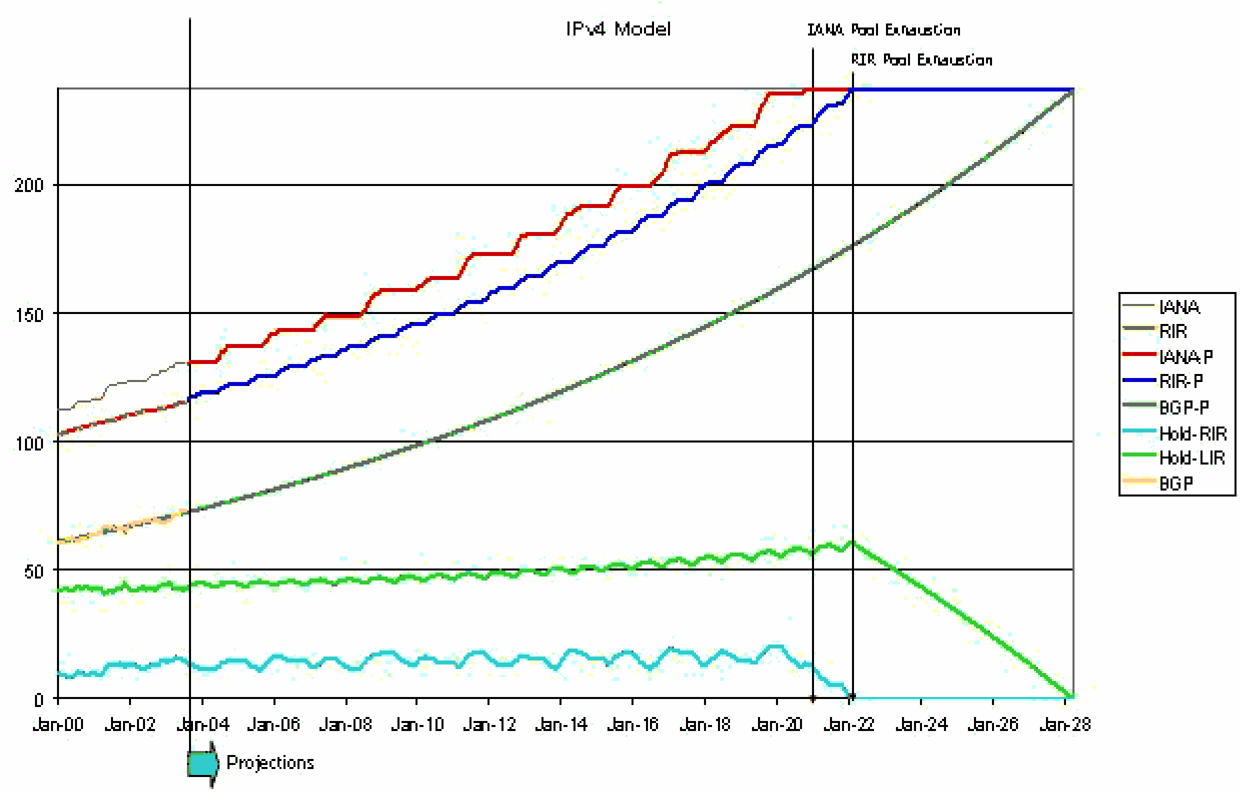
2. The amount of address space held by the RIR's grows slowly over time. There is a shorter period of oscillation imposed upon this pool, as each RIR will receive a /8 allocation from IANA when it's existing managed pool is assigned beyond a set threshold (currently 80% assigned), and this additional allocated space is then assigned to the same level before a new IANA allocation is made to the RIR. The rationale for the gradual increase in the pool size again lies in the slowly increasing assignation inefficiencies associated with managing increasingly larger address pools.

From the sum of the BGP table size and the LIR holding pool we can derive the total RIR-managed address pool. To this number is added the RIR holding pool low size and it's low threshold where a further IANA-allocation is required. This allows a view of the entire system, projected forward over time, where the central driver for the projection is the growth in the network itself, as described by the size of the announced IPv4 address space.



It would appear that the point of effective exhaustion is the point where the RIR's exhaust available address space to assign. In this model, RIR exhaustion of the unallocated address pool would occur in 2022.

Uncertainties

Of course such projections are based on the underlying assumption that tomorrow will be much like today, and the visible changes that have occurred in the past will smoothly translate to continued change in the future. There are some obvious weaknesses in this assumption, and many events could disrupt this prediction.

Some disruptions could be found in technology evolution. An upward shift in address take up rates because of an inability of NATs to support emerging popular applications is a possibility. The use of personal mobile IP devices (such as PDA's in their various formats) using public IPv4 addresses would place a massive load on the address space, simply due to the very large volumes associated with deployment of this particular technology.

Other disruptions have a social origin, such as the boom and bust cycle of Internet expansion in the late 1990's and early 2000's. Another form of disruption in this category could be the adoption of a change in the distribution function. The current RIR and LIR distribution model has been very effective in limiting the amount of accumulation of address space in idle holding pools, and in allocating addresses based on efficiency of utilization and conformance to a workable hierarchical model of address-based routing. Other forms of global resource distribution use a geo-political framework, where number blocks are passed to national entities, and further distribution is a matter of local policy (such a system is used in the E.164 number space for telephony). The disruptive nature of such a change would be to immediately increase the number of 'holding' points in the distribution system, locking away larger pools of address space from being deployed and advertised and generating a significant upward change in the overall address consumption rates due to an increase in the inefficiency of the altered distribution function.

From the perspective of a market rationalist there is a certain contrivedness about the Internet's address allocation process. The current address management system assumes a steady influx of new addresses to meet emerging demands, and the overall address utilization efficiency is not set by any form of market force, but by the outcomes of the application of RIR address allocation policies to new requests for space. The RIR perspective is that such policies are the outcome of an open process of industry self-regulation, and that these are a reflection of consensus-based determination of objectives in address management, and that addresses are not property and have no intrinsic value. Our market rationalist could well point to the prevalent use of market price as a means of determining the most economically efficient utilization of a commodity product. Such a position is based on the observation that the way that the consumer chooses between alternative substitutable services is by a market choice which is generally highly price sensitive. By removing price from an IPv4 address market the choices made by market players are not necessarily the most efficient choices, and some would argue that the current situation under prices IPv4 at the expense of IPv6.

However in venturing into these areas we are perhaps straying a little too far from exploring the degree of uncertainty in these predictive exercises, and a discussion of the interaction between various forms of distribution frameworks and likely technology outcomes is perhaps a topic for another time.

So just how long has IPv4 got?

Assuming a smooth continuity of growth in demand where growth rates are proportional to the size of the Internet, and assuming a continuation of the current utilization efficiency levels in the Internet, and assuming a continuing balance between public address utilization and various forms of address compression, and assuming the absence of highly disruptive events, then it would appear that the IPv4 world, in terms of address availability, could continue for another two decades or so without reaching any fixed boundary.

Is the IPv4 sky falling? A further two decades out is way over the event horizon for any form of reliable prediction in this business. So if we restrict the question to at most the next decade, then we can answer with some level of comfort that there is really no visible evidence of IPv4 exhausting it's address pool within this timeframe.

Or at least that's the way I read the cracks in my Oracle Bone!

Disclaimer

The above views do not represent the views of the Internet Society, nor do they represent the views of the author's employer, the Telstra Corporation. They were possibly the opinions of the author at the time of writing this article, but things always change, including the author's opinions!

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