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**Innovation in Internet Routing and Addressing**  
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Abstract

Despite the stability of the Internet technology, tremendous advances and important innovation are always happening. In particular, routing and addressing have profoundly changed during the years, with interesting research still ongoing and engineers willing to be heard about recent advances that may solve their operational problems. However, researchers and engineers lack a dedicated forum where they can meet and interact to discuss about routing and addressing. This document advocates the creation of such forum, to bring together these communities (researchers and engineers) and offer a dedicated venue.

Status of This Memo

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## **[1.](#) Driving Internet Innovation through Research on Routing and Addressing**

Despite the fact that the IP addressing and IP routing models have remained stable for more than 40 years, the Internet has experienced a huge evolution ever since. Even if later than expected, the transition from IPv4 to IPv6 is finally happening, showing that the Internet is able to make important leaps. Beyond such evolution, other very important innovations have been introduced by the IETF or are under active engineering development (e.g., SRv6 [[RFC8986](#)], MANET [[RFC2501](#)], 6LowPAN [[RFC4919](#)], ICN [[RFC7927](#)], PCE [[RFC4655](#)]).

The research community has also made important progress in better understanding the properties of the routing and addressing and also exploring diverse possible evolutions. Some of them being relatively disruptive, but worth to be considered. Such extraordinary work has been also recognized by the IRTF, where 18 out of 61 (circa 29%) of the Applied Networking Research Prize Awards have been granted to routing-related papers. All of the main academic conferences in networking, like [[INFOCOM](#)], [[SIGCOMM](#)], and [[CONEXT](#)] have sessions dedicated to routing and addressing, but also workshops fully dedicated to such topics ([[I-D.galis-irtf-sarnet21-report](#)], [[FIRA2022](#)]). Quite a number of multi-year and multi-million projects have been funded by government entity specifically on routing,



addressing, or more generally on architectural evolution of the Internet ([[EU-FIA](#)], [[NSF-FIA](#)]). A more thorough survey on research on routing, in the last decade or so, can be found in [[I-D.king-irtf-semantic-routing-survey](#)].

Communication scenarios have also evolved through the years. In the 90s the killer application was the World Wide Web. It remains a main use case of the Internet, but in the meantime several diverse communication scenarios have and still are emerging ([[BEZAHAF20](#)], [[LIU20](#)], [[BALAKRISHNAN21](#)], [[CAMPISTA14](#)]). While, the network layer remained focused on identifying communication end-points through addresses and determining paths between end-points through routing, the research, pushed by these new communications scenarios, has started to explore even more alternatives. In particular, investigating the possibility to add some semantic to addresses (not just for end-point identification [[I-D.jia-intarea-scenarios-problems-addressing](#)][[I-D.jia-intarea-internet-addressing-gap-analysis](#)]) and developing semantically rich routing (not strictly based on addresses and prefixes but also on other information, not necessarily from the network layer [[I-D.farrel-irtf-introduction-to-semantic-routing](#)]).

The evolution described above, has to continue and it is of paramount importance that it does not slowdown, in order to cope with future use and business cases, overcoming the existing challenges [[I-D.king-irtf-challenges-in-routing](#)] and going beyond mere reachability [[I-D.trossen-rtgwg-routing-beyond-reachability](#)].

## **2. From Research to Engineering**

Bringing consolidated research to the Internet is in general a hard task involving a lot of interaction between researchers and engineers. The former trying to abstract from the details of the real problem, while the latter trying to adapt the research outcome to the real context. This creates a sort of contention that only continuous information exchange can solve. Early engineering deployment are usually done in small size limited domains, which are then interconnected. In the remaining of this section we first look at how this "limited domains" approach helps innovation and then show-case few examples.

### **2.1. Bringing Innovation to life**

As previously mentioned, it is very common to bringing new solutions to the Internet through an incremental deployment that at early stages is very "limited" in size and secluded in dedicated and controlled "domains". Limited domains have been formally defined in [[RFC8799](#)], but they existed informally for a long time, helping introducing innovations in the Internet. In a certain way they are a



fact of (Internet) life. Historically, the Internet emerged as a limited domain, implementing the requirements and behaviors of its originating stakeholders. Even early IPv6 deployments were nothing more than interconnected limited domains (at that time called "island" in the IPv4 Internet). Today, it provides the common backbone for other limited domains, or, stated differently, provides the common foundation for further innovation. Indeed, private technologies isolated in a standalone domain are just less interesting, while interconnecting new solutions through the Internet, at different scale (cf. [Section 5 \[RFC8799\]](#)), is where innovation spurs. As [Section 4 of \[RFC8799\]](#) shows, the Internet and IETF's work contains a lot of technologies being deployed using such limited domains model, like for instance DiffServ [\[RFC2474\]](#), IntServ [\[RFC2205\]](#), Service Function Chaining (SFC) [\[RFC7665\]](#), Data Center Networks (DCN) overlays [\[RFC8151\]](#), Segment routing [\[RFC8402\]](#), to cite a few.

The limited domain deployment model enables research to become reality through implementation and deployments, with requirements and behaviors of stakeholders interested in solutions driving LD development. Example of requirements and behaviors are:

- \* New capabilities: traffic steering, better/different security, privacy, supporting different topologies, and mobility;
- \* Diverse technologies: routing on new identifiers (services, host, etc.), routing on different network layers like in IoT, and semantically enriched routing;
- \* Deep programmability: match-action capability of programmable data planes and advances in software and hardware enabling more complex packet processing;
- \* Innovation: Limited Domains enable incremental deployability in isolated islands for innovative solutions, which may or may not percolate to the whole Internet at later stages;
- \* Better QoS: provide some form of service differentiation which may be compatible to the best effort model (e.g., MPTCP [\[RFC8684\]](#), ALTO [\[RFC7285\]](#), Interconnected Traffic-Engineered Networks [\[RFC7926\]](#), or may rely on communication model radically different from the best effort model (e.g., DetNet [\[RFC8655\]](#), RAW [\[I-D.ietf-raw-use-cases\]](#)).



## **2.2. Examples of Routing and Addressing Innovation**

Hereafter, we briefly overview a few interesting examples of routing and addressing innovation that emerged (or is still emerging) as an interconnection of limited domains. The examples have been selected in no particular fashion or purpose beyond their self-explanatory nature. Certainly, quite a number of examples could be proposed, however there is no intention to be exhaustive here.

### Content Delivery Networks (CDN)

CDNs and CSP (Content Service Providers) have long ago recognized the existence of the need for interconnecting (previously) standalone CDNs so they can interoperate and collectively behave as a single delivery infrastructure [[RFC6707](#)]. That is why the CDNI WG ([[CDNIWG](#)]) has been formed in the IETF.

From the charter:

"...to allow the interconnection of separately administered CDNs in support of the end-to-end delivery of content from CSPs through multiple CDNs and ultimately to end users..."

This is a very interesting approach to innovation. While each CSP is free to develop their own technology, a general protocol is defined in order to safely interconnect different limited domains, not necessarily exposing internal policies and solutions [[RFC7337](#)]. This in turn triggers further innovation, like moving content closer to customers while maintaining a high level of security [[LELOUEDEC21](#)], or introducing specific technology like OpenFlow to deliver content across the Internet [[CHANG12](#)]

### Internet of Things (IoT)

IoT actually has different meaning in different contexts, however, IoT deployments better than any other technology shows how innovation is facilitated by using deployments limited domains. For instance, 6Lo(WPAN): define a Limited Domain that has:

- a specialized addressing architecture ([[RFC6775](#)]),
- a specialized neighbor discovery ([[RFC6775](#)], [[RFC8505](#)]),
- a specialized compression schemes ([[RFC6282](#)], [[RFC8138](#)]),
- a specialized routing protocol ([[RFC6550](#)]).





Scattered domains of this type can then be interconnected through the so called 6LowPAN Border Routers (6LBR [[RFC8929](#)]), basically bridging the limited domains into one. This is just an example of constrained node networks ([[RFC7228](#)]) that will help building smart cities in the coming years ([[CAN018](#)]). Beyond smart cities, thanks to IoT, there is an increasing digitalization in various non-ICT sectors, like for instance energy, healthcare, transportation [[NIZETIC20](#)].

## Privacy and Security

In recent years, people are developing a growing awareness about privacy and security issues [[PRIV-TRENDS](#)]. This is reflected in new regulations (e.g., General Data Protection Regulation - GDPR [[GODDARD17](#)]), but also privacy awareness in protocol design [[RFC6973](#)].

For private and secure communications a widely used approach are mix networks (e.g. [[TOR](#)]). In this context, each node can be seen as independent, untrusted, and interconnected through an untrusted network. Mix networks offer the highest privacy level at the cost of reduced performance (latency and/or bandwidth). Further, the principles and technology are used also for other emerging use cases (e.g. [[OSMAN21](#)], [[NEDELTCHEVA19](#)], [[ICLOUD](#)]).

Recently, Gartner coined the term "SASE" for "Secure Access Service Edge" [[SASE](#)], defining products and services aiming at securing the remote access of users or applications to enterprise resources (think about VPN on steroids). SASE is another kind of private/secure domain that needs to interface with the public Internet and enterprise cloud services, hence acting actually as an in-between limited domain.

Isolating mix networks and SASE solutions from the Internet (while using it as an interconnecting backbone) allows to develop innovative solutions that do not necessarily rely on privacy and security mechanisms of the public Internet, hence better tailored for their specific requirements, and is defining the future of network security ([[WOOD20](#)], [[DESHPANDE21](#)]).

## Industry 4.0

Today networked, smart factories are going beyond the limits of physical production lines. Smart manufacturing, marries physical production and operations with smart digital technology, machine learning, and big data to create a more holistic and better connected ecosystem for companies ([[SANCHEZ20](#)], [[WANG15](#)]).



Such eco-system is, in terms of manufacturing, the interconnection of different (limited) domains, namely the entire operation-- inventory and planning, financials, customer relationships, supply chain management, and manufacturing execution, etc. Such pervasive connectivity is expected to trigger the 4th revolution in the industrial world (hence the name Industry 4.0).

One way to move toward this vision is the adoption of the digital twin paradigm, or going beyond the best-effort model of the Internet. By providing a live copy of physical systems, digital twins bring to the table numerous advantages such as accelerated business processes, enhanced productivity, and faster innovation with reduced costs. However, this comes with strict requirements from a networking perspective, such as low latency and deterministic communication [[MASHALY21](#)]. Deterministic communication in particular is one of the major requirements in various industrial sectors [[RFC8578](#)]. However, such communication model may have profound implications in terms of routing, addressing, and security, substantially differing from the (best effort) Internet ([[BIG021](#)], [[MADDIKUNTA21](#)], [[SCANZIO21](#)]).

### **3. Interplay between Researchers and Engineers**

Scientific research and engineering innovation are able to progress because they are tight together in a loop and nurturing each other, as depicted in Figure 1. On the one hand, researchers take concrete problems that engineers need to solve, perform an abstraction so to get rid of unnecessary details, and solve the corresponding abstract problem. On the other hand, engineers take the solution to the abstract problem and adapt it to their specific context. Any mismatch or issue in this process is solved through more interaction.



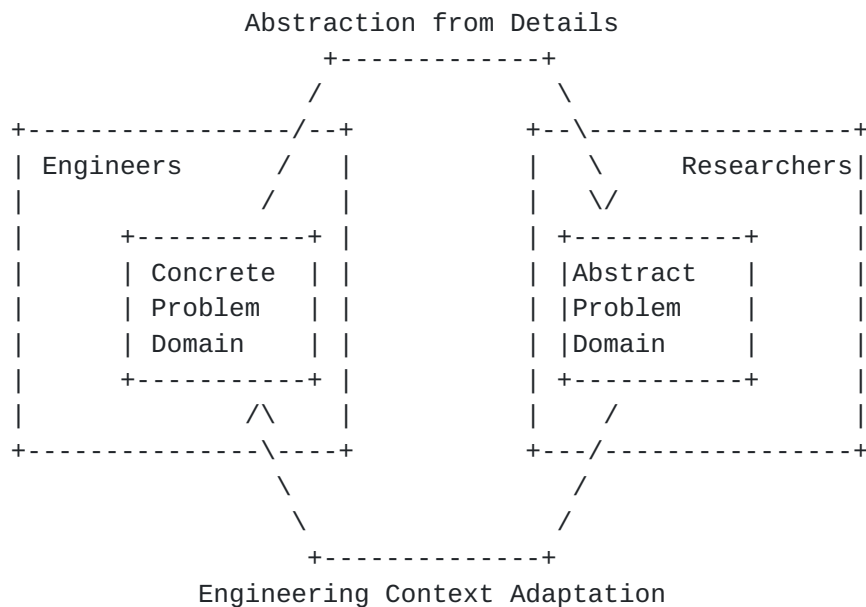


Figure 1: The Researchers<->Engineering innovation loop.

Research community and engineering community are not actually separate (like in Figure 1), but rather overlapping. Numerous researchers regularly participate to various SDOs to bring their solutions, and similarly, numerous engineers participate in academic conferences and research work to bring their "real world" experience. However, there is also some fragmentation, mirrored in the way the Internet evolves. On the one hand, community of researchers orbiting around specific conferences are certainly different depending on the conferent, yet not necessarily disjoint. For instance, the conferences IEEE INFOCOM, ACM SIGCOMM, and ACM SIGMETRICS, while being all top notch networking conferences, they represent three different type of researchers, IEEE INFOCOM more system oriented, ACM SIGCOMM more protocol oriented, and ACM SIGMETRICS more system theory oriented. On the other hand, something similar happens in SDOs. For instance, IEEE, 3GPP, and the IETF, all have network standardization activities but they tackle different aspects, where IEEE is more about link layer standards, 3GPP designs the different generations of cellular networks, and the IETF playing a key role on everything around the TCP/IP protocol suite. Yet, those SDOs do not attract necessarily the same engineering communities.

In order to keep up with innovation there is a need to ensure that the information between the various research communities and the various engineering communities flows smoothly, through continue interaction, exchange of opinions, experiences, problems, and viewpoints. This is certainly true in any field, including routing and addressing.



#### **4. Need to Amplify the Dialogue**

Deploying and interconnecting new solutions is not just about using the right interconnection protocol, it is also about "good" design. This raises a tussle between the Internet and innovation. On the one hand, the Internet is a well-functioning system whose core design represents sunk investments. Furthermore, changing a running system is pretty hard. On the other hand, there is an undeniable need for sustaining innovation, because of emerging communication scenarios where new stakeholders do not see their requirements adequately realized.

Increasingly widening stakeholder interests will continue to drive research and innovation (often in limited domain development). The interconnection is increasingly done based on various field/information with semantics that can be found, added, associated to an IP packet. The challenge lays in how to enable more innovation to be carried across to other limited domains or the Internet? How to share information about evolutions that are not harmful to the overall system?

Business as usual is not enough to answer the above questions. If there is not enough information sharing there is a risk to see a fragmented evolution, due to independent innovation carried out in the different communities mentioned above. Such a fragmented evolution may create some risks, like for instance:

- \* Too many scattered unrelated domains interconnecting through the Internet may actually hamper Internet robustness and its lean design.
- \* Too many ad-hoc solutions/building blocks lead to high complexity and augmented fragility.
- \* The need for 'offset' operations may decrease overall efficiency.
- \* The desire for a common denominator (IPv6 plus associated routing) affects all interconnected domains, possibly impacting performance and ultimately innovation capability.
- \* Nodes behavior gets more complicated, particularly at domain boundaries, leading to unexpected/unwanted behavior, like:
  - semantic leakage, i.e., routing information, leading to fragility or security issues;
  - privacy related information leakage that is pertinent for security (e.g., sensors' MAC addresses or user identifiers);





- Specific technology islands may become more isolated, therefore hampering interconnection and interoperability.

## 5. Time is Right to make it Right

It can be observed that "The Time is Right to make it Right", because we are at a juncture point.

The Internet technology is quite mature connecting a huge number of networking technologies and providing global connectivity. Actually, the TCP/IP protocol stack is so mature that is becoming commodity, hence the fragmented evolution previously mentioned. While TCP/IP is the more and more the converging technology, services are differentiating, raising the need for making the Internet to continue to evolve as well. When IPv6 started to be discussed, there was a general sense of "urgency", because of the address shortage forecasted by early 2000s (this was before NAT). This lead to some conservative choices in order to somehow smooth the transition. In this point in time, we have the luxury not being in such an situation, there is no need to hurry up, instead there is the opportunity, which we hopefully will not miss, to take the time to carefully think about how to structure the unstructured by looking forward.

## 6. The role of the IETF

As mentioned in [Section 1](#), the IETF has always worked in introducing important innovations in the Internet so to make it evolve and adapt to the different emerging use cases. More importantly, the IETF has recognized the importance of the interaction between researchers and engineers a long time ago when its research branch, namely the Internet Research Task Force ([\[IRTF\]](#)) was created.

### 6.1. Enter the IRTF

The IRTF has a privileged position close to the engineering community, and already in [\[RFC2014\]](#), the first document setting the IRTF guidelines, the importance of making engineers discuss with researchers was recognized:

"... The expectation is that by sponsoring Research Groups, the IRTF can foster cross-organizational collaboration, help to create "critical mass" in important research areas, and add to the visibility and impact of the work. ... "

Figure 2 tries to position the IRTF in the researchers<->engineering innovation loop previously presented. Clearly the IRTF, has a central role, helping in formalizing real problems and requirements,



so that afterwards an abstraction of the former can be tackled by researchers. The IRTF can then help deciding whether the resulting solution is mature enough to be transferred in the engineering domain by first deriving detailed specifications so to facilitate later on the adaptation to the engineering context.

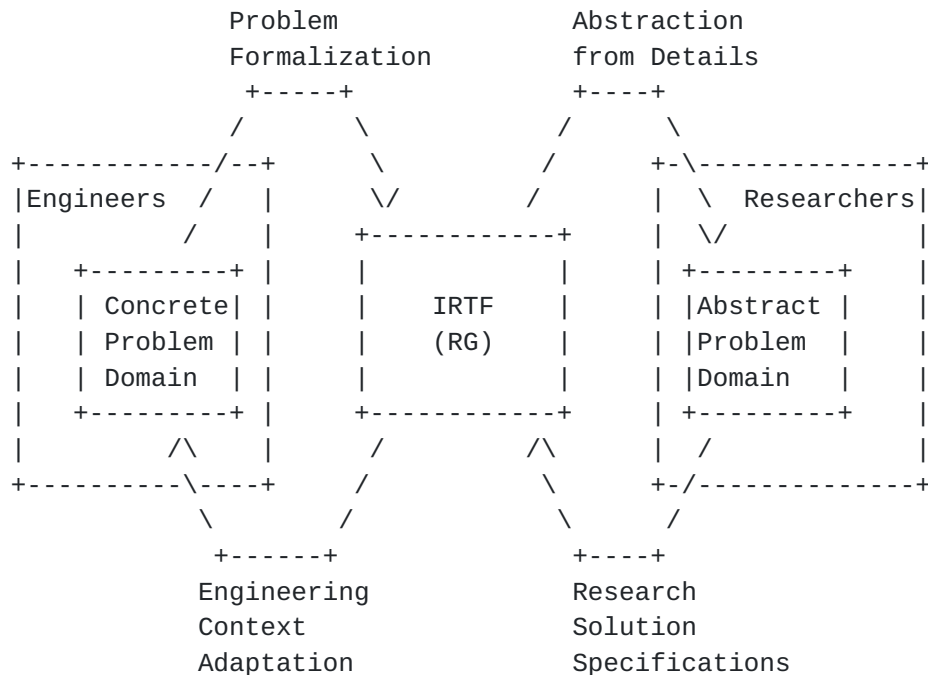


Figure 2: The role of IRTF in the Researchers<->Engineering innovation loop.

## 6.2. Routing and Addressing in the IRTF

Because of the above-mentioned role of the IRTF it is worth to have a better look at the activities related to routing and addressing. However, before overviewing such activities, it is important noting that because routing and addressing are cornerstones of the protocol stack

- \* everything relates to routing and addressing,
- \* routing and addressing relates to everything.

In other words, any IRTF's research group may include routing/ addressing aspects and/or discuss them in the scope of their specific topics. In the following, there is an attempt to class the various Research Group as more or less related to routing and addressing, so to understand whether or not they can be considered a potential venue to discuss Routing and Addressing in general. When referring to specific Research Groups, the text following the name of the



research groups listed below is an excerpt of their charter. Three classes are identified, namely:

- \* A) Almost unrelated: the RG will rarely (if ever) discuss about routing and addressing.
- \* B) Lightly related: the RG may touch some routing and addressing aspects as side effects of their specific topic.
- \* C) Tightly related: routing and addressing is explicitly mentioned in the charter and are part of the research discussed in the group.

The following research groups can be considered as part of class A (almost unrelated to routing and addressing):

- \* [[CFRG](#)] - Crypto Forum Research Group: Forum for discussing and reviewing uses of cryptographic mechanisms.
- \* [[GAIA](#)] - Global Access to the Internet for All Research Group: Internet access considered a basic human right.
- \* [[NWCRG](#)] - Network Coding for Efficient Network Communications Research Group: Research Network Coding principles and methods that can benefit Internet communication.
- \* [[MAPRG](#)] - Measurement and Analysis for Protocols Research Group: Forum being a "landing pad" for the Internet measurement community to introduce its efforts to the IETF.
- \* [[QIRG](#)] - Quantum Internet Research Group: Quantum secure communication, distributed quantum computing, and quantum-enhanced physical sensor systems.
- \* [[HRPC](#)] - Human Rights Protocol Considerations Research Group: Research whether standards and protocols can enable, strengthen or threaten human rights.
- \* [[ICCRG](#)] - Internet Congestion Control Research Group: To move towards consensus on which technologies are viable long-term solutions for the Internet congestion control architecture.

The following research groups can be considered as part of group B (lightly related to routing and addressing):

- \* [[DINRG](#)] - Decentralized Internet Infrastructure Research Group: Research on decentralizing infrastructure services such as trust



management, identity management, name resolution, resource/asset ownership management, and resource discovery.

- \* [\[PEARG\]](#) - Privacy Enhancements and Assessments Research Group: General forum for discussing and reviewing privacy enhancing technologies for network protocols and distributed systems in general, and for the IETF in particular.
- \* [\[NMRG\]](#) - Network Management Research Group: Forum to explore new technologies for the management of the Internet. Such as communication services between management systems, which may belong to different management domains, as well as customer-oriented management services.
- \* [\[ICNRG\]](#) - Information-Centric Networking Research Group: Introducing uniquely named data as a core Internet principle. Data becomes independent from location, application, storage, and means of transportation, enabling in-network caching and replication.
- \* [\[PANRG\]](#) - Path Aware Networking Research Group: Forum in support of research aiming at bringing path awareness to transport and application layer protocols.
- \* [\[T2TRG\]](#) - Thing-to-Thing Research Group: Research forum to investigate open research issues in turning a true "Internet of Things" into reality, an Internet where low-resource nodes ("things", "constrained nodes") can communicate among themselves and with the wider Internet, in order to partake in permissionless innovation.
- \* [\[COINRG\]](#) - Computing In the Network Research Group: To explore existing research and foster investigation of "compute in network" and resultant impacts to the data plane.

The above lists, include all existing RG at the time of this writing, and no RG has been identified as belonging to class C (tightly related to routing and addressing). The clear takeaway is that there is no research group in the IRTF that has an explicit focus on innovation in the specific context of routing and addressing.





## **7. Discussing Routing and Addressing Innovation**

Previous sections have highlighted how the present situation is that routing and addressing research and innovation are discussed a little bit in numerous places (conferences and SDOs), but have not a dedicated forum. Yet, there are still challenges to take up and certainly would not harm thinking to the long term evolution of the the cornerstones of the Internet.

In order keep the research and the innovation in routing and addressing consistent and ongoing, avoiding a fragmented evolution, as described in the first part of the present memo, a specific dedicated forum should exists.

It looks judicious to have such a forum created in the IRTF, chartered to encourage research and debate into routing systems and architectures, where a major role of the chairs would be to reach out in the research community to bring in people that do not usually attend IETF/IRTF meetings, whose research may fall under the radars of the engineering community.

Paraphrasing the MAPRG charter: being a "landing pad" for the Internet routing and addressing community to introduce its efforts to the IETF.

## **8. Sign the Manifesto**

If you agree that the kind of forum described above should exist and make the above-listed meetings a regular event, please add your name to the public list of supporters at:

<https://etherpad.wikimedia.org/p/routing.addressing.manifesto>

expressing the willingness to create, participate and contribute to such a forum.

Alternatively, send an email at the address:

routing.addressing.manifesto@gmail.com

The editor of the draft will take care to add the information provided by mail to the public list of supporters.

## **9. Security Considerations**

The present memo does not introduce any new technology and/or mechanism and as such does not introduce any security threat to the TCP/IP protocol suite.



## **10. IANA Considerations**

This document includes no request to IANA.

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