The Dynamics of A Self-Forming Network

Igor Sobrado and Dave Uhring

Abstract—This article describes our strategy for deploying self-forming ad hoc networks based on the Internet Protocol version 6 and evaluates the dynamics of this proposal. Among others, we suggest a technique called adaptive routing that provides secure intelligent routing capabilities to computer communication networks. This technique uses the flow label, supports hybrid metrics, network load sharing, and is not restricted to evaluation of performance on first hop routers when making routing decisions. Selective anycasting is an extension to the anycast addressing model that supports exclusion of members of groups that perform poorly or inappropriately on a per-host basis. Distributed name lookup is suggested for integrating self-forming and global networks where they coexist. At last, we pose an address hierarchy to support unmanaged discovery of services in unknown networks.

I. INTRODUCTION

SELF-FORMING ad hoc computer networks [1] will become an active research field in the coming years. As other self-organizing networks, these networks are able to respond to hostile actions such as Denial of Service (DoS) and Distributed Denial of Service (DDoS) attacks more efficiently than traditional networks. This ability is useful for deploying unmanaged computer networks. Self-forming networks are an adequate platform to deploy proposals like intelligent autonomous agents [2] that require some degree of survivability in the network infrastructure.

A fault tolerant network like the one suggested above requires intelligent routing capabilities and a technique for discovering and allocating resources in an unmanaged and non-centralized way. Requirements include:

- Reliable, fault tolerant, communication networks supporting an intelligent routing framework and redundancy;
- Discovery of devices offering services in a dynamic networking environment, in an unmanaged way;
- Integration with existing network infrastructures where available, supporting a world-wide reaching technique;
- Automatic configuration of devices; and, finally,
- A secure network infrastructure.

In this paper we propose a technique, called adaptive routing, that provides secure intelligent routing capabilities to computer networks at an autonomous system (AS) level. This technique, based on the use of the flow label field, resolves the security issues associated with other routing proposals in a simple and elegant way. Selective anycasting increases the robustness of anycast addressing, enabling hosts to selectively reject those members of anycast groups that do not fit their requirements but are still alive.

The most important contributions of this manuscript are the development of a secure intelligent routing infrastructure for computer communication networks, and an extension to anycasting that significantly increases the robustness and reliability of this addressing model. Discovery of services and a distributed name lookup mechanism, presented initially in [3] for the automatic configuration of IPv6 devices, is applied to self-forming networks.

The remainder of the paper is organized as follows. In Section II we introduce related work. Section III describes the notational conventions used in this article. Section IV outlines our proposal for deploying self-forming ad hoc networks at a theoretical level. Section V provides a performance evaluation of our prototype when compared with current fixed networks. Section VI presents the security weaknesses commonly found on ad hoc networks and, more specifically, self-forming networks, and how our proposal manages those security issues. Some possible research lines are shown in Section VII. Finally, conclusions are outlined in Section VIII.

II. RELATED WORK

The Internet Protocol version 6 (IPv6) [4], [5] is a good foundation for deploying self-forming computer networks. This communication protocol provides hierarchical addresses and is a key element for supporting safe intelligent routing using the flow label field. This section provides an overview of research efforts related with our proposal.

- The Dynamic Host Configuration Protocol (DHCPv6) [6] allows passing configuration parameters such as network addresses, netmasks, and hostnames to network nodes from a DHCP server.
- The flow label field [7] enables classification of packets belonging to a specific stream by the \( (label, src, dst) \) triplet. This field can be used by the packet classifier in a router to efficiently forward traffic for a particular data stream. As routers do not need to parse the option headers, packets can be processed faster, increasing effective routers throughput.
- Intelligent route controllers [8]–[10] are appliances that make routing decisions for multi-homed connections implementing route changes in Border Gateway Protocol (BGP) [11] routers. Currently, non-BGP routing is a cost effective solution for networks that do not want to run a routing protocol as complex as BGP. An intelligent route controller optimizes traffic routed from a subset of the Internet address space to a set of non-overlapping regions called clusters.
- The Internet Control Message Protocol (ICMPv6) [4] REDIRECT messages are used by routers to inform other nodes of a better first hop toward a destination. Considered harmful by security concerned sites, REDIRECT messages are not honored by most routers.
**TABLE I**

**NOTATIONAL CONVENTIONS USED IN THIS PAPER**

| Symbol | Definition |
|--------|------------|
| \( \mathcal{P} = (p_0; p_1, p_2, \ldots, p_n) \) | set of parameters that define the requirements of a packet stream; \( p_i \) is the weight of the \( i \)-th parameter |
| \( \mathcal{R}_i = \{ r_{i,1}, r_{i,2}, \ldots, r_{i,n_i} \} \) | \( i \)-th route discovered in the ad hoc network; \( r_{i,j} \) is the \( j \)-th intermediate system in the route; \( n_i \) is the number of intermediate systems in that route |
| \( r_i \rightarrow r_j \) | link between intermediate systems \( r_i \) and \( r_j \) |
| \( w^j(p_0; p_1, p_2, \ldots, p_n) \) | total cost of the \( i \)-th route |
| \( w^j_i(p_1, p_2, \ldots, p_n) \) | cost of the \( j \)-th intermediate system, \( r^j_i \) |
| \( w_{opt}(p_0; p_1, p_2, \ldots, p_n) \) | lower cost found |

*For example: bandwidth, latency, number of hops...*

- The routing extension header [12] is an IPv6 header option used to route packets, either strictly or loosely, from a source to a destination host. It is assumed that, as the ICMPv6 REDIRECT messages, the routing header is a security concern as a consequence of a lack of an authentication mechanism.

As a difference with intelligent route controllers, we propose making intra-AS routing decisions. Our proposal is intended to complement, not to replace, intelligent route controllers. From all the above, we conclude that both the ICMPv6 REDIRECT messages and the routing extension header are not adequate mechanisms to achieve intelligent routing. Instead, we suggest using a secure mechanism to modify the interface to which a flow label is assigned.

### III. NOTATIONAL CONVENTIONS

Let us define the set of intermediate systems in the \( i \)-th route discovered by the route servers as \( \mathcal{R}_i = \{ r_{i,1}, r_{i,2}, \ldots, r_{i,n_i} \} \), where \( r_{i,j} \) is the \( j \)-th intermediate system in this route. Routes are calculated to minimize the cost, \( w^j \), for a set of parameters \( \mathcal{P} = (p_0; p_1, p_2, \ldots, p_n) \). In this paper \( r_i \rightarrow r_{i+1} \) denotes a link between intermediate systems \( r_i \) and \( r_{i+1} \). This link is not bidirectional; in other words, \( r_{i+1} \rightarrow r_i \) is a different link in our simulation. We pose the notation \( r_i \leftrightarrow r_{i+1} \) to denote both links simultaneously. A brief outline of notational conventions used in this manuscript is provided in Table I.

### IV. ADAPTIVE COMPUTER NETWORKS

One of the goals of a self-forming ad hoc computer network is being able to respond to a changing environment (e. g., degrading softly under a DoS attack). Both automatic discovery of services and adaptive routing are powerful tools for responding to the challenges introduced by dynamic network topologies. The former is based on the use of reliable anycast groups and service oriented IPv6 addresses; the latter on route servers (RSes) and flow labels. We suggest using a distributed name service for integration between self-forming and fixed networks. This naming service allows nomadic networks to be reachable without using tunnels. The use of a local namespace on each device for allocating services discovered simplifies application management.

#### A. Discovery of Services

As outlined in [3], anycasting [13], [14] with service oriented IPv6 addresses\(^1\) can be used to build a framework for the automatic discovery of machines offering services. The unicast addresses of those machines can be added to local namespaces in each self-configurable device to simplify configuration of applications. Selective anycasting, described below, can greatly improve reliability of anycast addressing.

#### B. Overlay Networks

**Distributed name lookup (DNL)** [3] is a name resolution technique useful for reaching nodes of a self-forming nomadic network where access to a global communication infrastructure is possible. DNL splits name resolution in two tasks that will run on probably different nameservers. In fact, DNL makes forward resolution in the base network (i. e., the network of the mobility provider) and reverse translation in the network where the mobile devices reside. These temporary resource records cannot be transferred to slave nameservers.

#### C. Adaptive Routing

We suggest using RSes, supporting hybrid metrics for route optimization, and an intelligent routing based on the flow label field. Hybrid metrics allow routing infrastructure to assign a cost to each intermediate system that depends on more than one parameter. Each parameter can have a different weight in the estimation of the cost.

1. **Combining Multiple Metrics in a Single (Hybrid) Metric:**

RSes can assign a cost to each intermediate system as a function of the requirements for packet forwarding for a given data stream (e. g., high bandwidth, low latency, ...). Let us define the total cost \( w^j(p_0; p_1, p_2, \ldots, p_n) \) for a route \( \mathcal{R}_j = \{ r_{j,1}, r_{j,2}, \ldots, r_{j,n_{j}} \} \) as:

\[
\textstyle\sum_{i=1}^{n_{j}} w^j_i(p_1, p_2, \ldots, p_n) \triangleq \text{def} \frac{p_0}{b^j} + \sum_{i=1}^{n_{j}} w^j_i(p_1, p_2, \ldots, p_n) \tag{1}
\]

where \( \mathcal{P} = (p_0; p_1, p_2, \ldots, p_n) \) is a set of parameters that define the requirements of the hybrid metric; in this equation,

\[
b^j \triangleq \min_{1 \leq i \leq n_{j}} b^j_i \tag{2}
\]

is the end-to-end effective bandwidth between the source and destination hosts \((b^j_i)\) is the available bandwidth in the intermediate system \( r^j_i \); \( w^j_i(p_1, p_2, \ldots, p_n) \) is the cost\(^2\) of \( r^j_i \) in the route \( \mathcal{R}_j \) for \( \mathcal{P} \). The best path discovered is the one that minimizes the end-to-end cost:

\[
w_{opt}(p_0; p_1, p_2, \ldots, p_n) = \min_{\forall j} w^j(p_0; p_1, p_2, \ldots, p_n) \tag{3}
\]

Table III shows a subset of end-to-end metrics that can be used to calculate the cost of a route between two hosts.

\(^1\)Where the host portion of the IPv6 address has been replaced by a service identifier field.

\(^2\)The weight assigned to the bandwidth requirement, must be applied to the effective bandwidth for the end-to-end route. This parameter cannot be applied to the throughput on each intermediate system.
TABLE II
METRICS FOR END-TO-END PERFORMANCE ESTIMATION

| Symbol | Quantity | Mathematical Expression for this metric | Units |
|--------|----------|-----------------------------------------|-------|
| $b^i$  | available bandwidth$^i$ | $b^i = \min_{1 \leq i \leq n_i} b^i$ | kB · s$^{-1}$ |
| multiple | communication cost | price, reliability, security, etc... | N/A |
| $t$    | delay$^b$ | $t = \sum_{i=1}^{n_i} t_i$ | s |
| $\Delta t$ | jitter$^c$ | $\Delta t = \sum_{i=1}^{n_i} \Delta t_i$ | s |
| $n_i$  | number of hops | N/A | none |

$^a$For file transfer protocols.
$^b$For interactive applications (e. g., TELNET).
$^c$For multimedia streams.

2) Routing Packets: Intelligent routing can usually be abused to gain access to networks whose firewalls are poorly configured. Therefore, routing decisions should not be made by untrusted third parties (e. g., hosts) but from authenticated devices. For adaptive routing, we suggest the use of RSes that will try to discover the route that best fits the set of requirements $P$ for a data stream between two nodes of the self-forming network. These devices must be authorized to modify the interface assigned to a flow label on routers. Routers supporting this feature are called adaptive routers in this article. Adaptive routers can monitor their network interfaces looking for communication failures; if a failure is detected, adaptive routers can ask an authorized RS for an alternative route to the destination host. RSes can use a keep-alive mechanism to ascertain the availability of adaptive routers. An adaptive router that stops responding to the requests of a RS is an indication of a network failure too.

3) Selective Anycasting: Let us suppose that one of the members of the anycast group is not performing as expected. The members of the self-forming network should have a chance to reject those members that does not. Existing keep-alive mechanisms cannot detect members that behave poorly or inappropriately but are still alive. Our proposal is using a members exclusion header (EH) to provide a list of machines that should not be contacted.$^3$ To protect clients of the self-forming network against variations in the routing path as a consequence of changes in the network topology, we suggest using the unicast addresses assigned to the members of the anycast group instead of its relative position in the routing path. Anycast addresses can be translated to unicast ones, using either anycast address mapper or the source identification option [15]. Each time an entry is added to the EH, a new data stream must be established; as a consequence, a new flow label is calculated by the source host. This header should be under the control of end-user nodes because:

- Routers are not designed for network analysis; and,
- Applications have the ability to decide if a member of an anycast group is performing adequately, and should have

$^3$As anycast addresses are assigned to routers [13] to simplify routing, this exclusion header does not require support in the members of the groups.

Selective anycasting is a lightweight extension to the anycasting addressing model that does not introduce overhead in routing if flow labels are used$^4$.

Fig. 1 outlines an analogy between selective anycasting and a simple mechanical set-up. Let us suppose that an incompressible Newtonian fluid flows in a continuous stream on the pipeline described in this figure. Joints in this pipeline are comparable to anycast routers. Each duct has a valve that acts as a control device for conveying the Newtonian fluid in the experimental device. These valves close temporarily an orifice that permits the movement of fluid to the “members of the anycast group”, in the lower part of the figure. Initially, all valves are open, allowing the incompressible fluid to convey to the nearest member of the anycast group from the point of view of the pipeline topology. In our analogy, adding the unicast IP address assigned to a member of the group to the EH is like closing the valve in the duct that joints that member to the main pipeline. Without those valves, the fluid that flows on the pipeline has no chance to be carried to other members of the anycast group. In our scenario nodes whose IP addresses are in the set $S = \{IP_1, IP_2, \ldots, IP_{n-1}\}$ had been excluded by closing the valves in the ducts that joint them to the pipeline. These nodes will not be reached until valves are open again (i. e., until their addresses are removed from the EH and a new packet stream to the anycast group is established).

V. EXPERIMENTAL EVALUATION

We used the $ns$ Network Simulator [16], [17] for testing the proposal outlined in this manuscript. Our prototype was developed using the Object Tcl [18] programming language, an extension to the Tool Command Language (Tcl) [19] for dynamic object-oriented programming. In this Section, we describe the experimental set-up used to test our intelligent routing model and provide performance metrics for our prototype when compared to standard routing proposals.

A. Description of the Prototype

The aim of our simulation is estimating the ability of our proposal to recover connectivity when compared to standard routing algorithms after a part of the network has been damaged; consequently, the network topology assures the existence of more than one valid route between the source and destination hosts. We simulate a damaged link between

$^4$Flow labels are required for adaptive routing, not for selective anycasting.
intermediate systems \( r_i \) and \( r_j \) by turning down the links \( r_i \leftrightarrow r_j \) simultaneously. Same failure conditions are applied for all routing proposals evaluated in this article.

![Diagram](image)

**Fig. 2.** Changing the Interface assigned to a Flow Label in our Prototype

Fig. 2 shows how we have implemented the flow label updating mechanism in *ns*. Let us suppose that an intermediate system \( r_i \) has two output interfaces, \( r_i \rightarrow r_{i+1} \) and \( r_i \rightarrow r_{i+1}^\sim \), both of them valid routes toward a destination host. To route traffic to one of these interfaces our prototype turns down all the output links except the one that will carry the data stream. In this scenario, both \( r_{i+1} \rightarrow r_i \) and \( r_{i+1}^\sim \rightarrow r_i \) remain up to allow acknowledgments (ACKs) reaching the host that has sent the packets through the link \( r_i \rightarrow r_{i-1} \). Our simulation uses a *distance vector* (DV) routing algorithm.

**B. Performance Evaluation**

The goal for our routing proposal is not performance but reliability. On the other hand, intelligent routing is a powerful tool for increasing network performance, allowing routing infrastructure to make routing decisions based on a global network state, instead of *first neighbors* feedback.

Figs. 3 to 8 illustrate the performance of TCP Reno, a *selective acknowledgment* (SACK) TCP sender, TCP Tahoe, TCP Vegas, and our adaptive routing proposal. Fig. 6 depicts network dynamics when a permanent link failure is detected by an adaptive router and announced to a RS. Scenario outlined in Fig. 2 is a variant of the previous one; in this case, both a standard router and an adaptive router are unreachable after the link failure. A higher delay in recovering network connectivity in the self-forming network is observed because a new route is not calculated by the RS before the keep-alive mechanism ascertains that the adaptive router is not available. Finally, Fig. 8 depicts the effect of a short loss of connectivity. When the adaptive route detects the network failure it sends a request to update the route followed by data streams to a RS. Both a *fast response* (FR) from the RS, received before connectivity is recovered, and a *slow response* (SR), received after recovering normal network conditions, are compared with the performance of TCP Reno in same network conditions.

**VI. Security Considerations**

Joining anycast and multicast groups in a secure manner [20], [21] is a requirement for supporting current networking services. Authentication of the members of anycast groups is required for discovery of services. Selective anycasting provides reliable and fault tolerant anycast groups.

Adaptive routing works for self-forming networks with an internal packet forwarding mechanism. It is a secure approach to intelligent traffic routing because:

1) The exact route is not under control of network nodes;
2) Only authorized RSes are able to change the route on the routers enabled to support this feature.

As both authentication of RSes and a relatively updated knowledge of network topology is required, intelligent routing must be done at an AS level. Contacting with anycast groups of RSes in other ASes allows this proposal to be extended to a global computer network like Internet.

**VII. Future Work**

We suggest improving the synchronization mechanism between adaptive routers and RSes. Detection of changes in the network topology as soon as occur is an important goal. The development of a keep-alive mechanism between RSes and adaptive routers will contribute to detection of network failures that isolate adaptive routers from the rest of the network.

**VIII. Conclusion**

Survival from failures in communication infrastructure and attacks against networking equipment requires development of robust, fault tolerant, computer communication networks. This article proposes some techniques to improve reliability of current communication frameworks and support construction of self-forming ad hoc computer networks. Our main contributions are:
The development of an anycast addressing extension to allow applications to reject those members of anycast groups that are not performing adequately, but are still alive; and,

A framework, based on IPv6 flow labels, that provides intelligent routing capabilities to computer networks.

Other techniques we have developed in the last years are suggested for integration with fixed networks and for the unattended configuration of devices.

ACKNOWLEDGMENT

The authors would like to thank Jerry O. Forté, the founder of Forté Computer Systems Inc., for providing us with the networking infrastructure required to perform this research. Lucas Fernández Seivane helped with an odd problem translating some figures to Encapsulated PostScript (EPS) format.

REFERENCES

[1] “Defense Advanced Research Projects Agency (DARPA) strategic plan,” February 2003.
[2] I. Sobrado, “Evaluation of two security schemes for mobile agents,” in Proc. of the 1st ACM SIGCOMM Workshop on Data Comm. in Latin America and the Caribbean. San Jose, Costa Rica: ACM, April 2001, reprinted in Supplement to Computer Comm. Review 31(2), April 2001.
[3] V. G. Garcia, I. Sobrado, and D. Uhrling, “On auto-configurable network devices,” in International Association of Science and Technology for Development (IASTED) 9th Conf. on Internet and Multimedia Systems and Applications (EuroIMSA), Grindelwald, Switzerland, February 2005.
[4] A. Conta and S. Deering, “Internet Control Message Protocol (ICMPv6) for the Internet Protocol Version 6 (IPv6) specification,” Request for Comments (RFC) 2463, December 1998.
[5] C. Huitema, IPv6: The New Internet Protocol, 2nd ed. Prentice Hall PTR, January 1998.
[6] J. Bound, B. Volz, T. Lemon, C. Perkins, and M. Carney, “Dynamic Host Configuration Protocol for IPv6 (DHCPv6),” Request for Comments (RFC) 3315, July 2003.
[7] J. Rajahalme, A. Conta, B. Carpenter, and S. Deering, “IPv6 flow label specification,” Request for Comments (RFC) 3697, March 2004.
[8] S. Borthick, “Route controllers: Fertile ground or field of dreams?” Business Comm. Review, March 2003.
[9] D. Passmore, “Multihoming route optimizers,” Business Comm. Review, November 2001.
[10] Z. Kerravala, N. Maynard, and A. Phull, “Intelligent routing: Bringing reliability to the Internet,” Analyst Corner, September 2002.
[11] Y. Rekhter and T. Li, “A Border Gateway Protocol 4 (BGP-4),” Request for Comments (RFC) 1771, March 1995.
[12] S. Deering and R. Hinden, “Internet Protocol Version 6 (IPv6) specification,” Request for Comments (RFC) 2600, December 1998.
[13] R. Hinden and S. Deering, “Internet Protocol Version 6 (IPv6) addressing architecture,” Request for Comments (RFC) 3513, April 2003.
[14] C. Partridge, T. Mendez, and W. Milliken, “Host anycasting service,” Request for Comments (RFC) 1546, November 1993.
[15] O. Masafumi and Y. Suguru, “Implementation and evaluation of IPv6 anycasting,” in Proc. of the 10th Annual Internet Society Conf., Yokohama, Japan, July 2000.
[16] L. Breslau, D. Estrin, K. Fall, S. Floyd, J. Heidemann, A. Helmy, P. Huang, S. McCanne, K. Varadhan, Y. Xu, and H. Yu, “Advances in network simulation,” IEEE Computer, vol. 33, no. 5, May 2000, expanded version available as USC TR 99-702b.
[17] S. McCanne and S. Floyd, “ns Network Simulator,” [Online] available at http://www.isi.edu/nsnam/ns/.
[18] D. Wetherall and C. J. Lindblad, “Extending Tcl for dynamic object-oriented programming,” in Proc. of the USENIX 3rd Tcl/Tk Annual Workshop, Toronto, Ontario, July 1995.
[19] J. K. Ousterhout, “Tcl: An embeddable command language,” in Proc. of the Winter 1990 USENIX Technical Conf., January 1990.
[20] L. Donseti, “Anycast security requirements,” in Internet Engineering Task Force (IETF) 12th Secure Multicast Group (SMuG) Meeting, Minneapolis, MN, March 2001.
[21] P. Judge and M. Ammar, “Gothic: A group access control architecture for secure multicast and anycast,” in Proc. IEEE INFOCOM 2002, vol. 21, no. 1. IEEE, June 2002.