USING STRUCTURED OVERLAYS TO CREATE DECENTRALIZED AND DISTRIBUTED APPLICATIONS

By

DAVID ISAAC WOLINSKY

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By

David Isaac Wolinsky

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Virtual private networks (VPNs) enable existing network applications to run unmodified in insecure and constrained environments by creating an isolated and secure virtual environment providing all-to-all connectivity for VPN members. VPNs are traditionally centralized, limiting applicability due to resource requirements and the incurred overhead of having all communication traversing the central server. In recent years, there has been a paradigm shift towards the use of peer-to-peer (P2P) communication in VPNs enabling direct communication amongst participants, alleviating pressure placed upon the central server relegating it to handling session management and supporting indirect communication by relaying traffic when NAT or firewall traversal fails. Unstructured P2P, though less studied, removes all centralization from the VPN with the cost of users having to manually create links amongst peers. An issue with existing VPN approaches is the lack of methods for certificate and certificate revocation handling and distribution requiring the user to employ their own solutions.

I propose a novel VPN using structured P2P overlays emphasizing their scalable and resilient nature and supporting a security framework that self-configures through a group-based public key infrastructure for user-friendly operation. Structured overlays enable users to deploy and maintain decentralized, distributed applications with limited need for centralization by ensuring fast seek time (typically $O(\log(N))$) when searching

for a node near a location in the overlay. The novel contributions of my work include a configurable virtual network architecture to support different aspects of reliability, performance, portability, and usability; a P2P security architecture integrating PKI with systems constrained by NATs and firewalls; user-assisted automated PKI enabled by group-oriented Web 2.0 interfaces; and the creation of virtual private overlays from existing public overlays to provide isolation and overlay security for the VPN. Furthermore, I plan on investigating how to support VPNs in environments where users lack administrative permissions through a sockets proxy using overlay-aware TCP, connecting those hosts to other VPN clients.

The premise for this work is to enhance the usability of VPN systems for non-expert users to use in home, small/medium business, and education environments as demonstrated by prototypes found in the SocialVPN, GroupVPN, Grid Appliance, and Archer projects. The SocialVPN creates user-centric VPNs so that peers only have VPN links with their social network friends, whereas the GroupVPN employs a group infrastructure to manage VPN members and distribute VPN configuration. A free GroupVPN bootstrapping environment relying on PlanetLab hosted resources has been available for over a year with already over hundreds of users. GroupVPN has been used by several universities to connect decentralized grids. The Grid Appliance uses the GroupVPN to form ad-hoc and decentralized computing pools, facilitating computer architecture research in the Archer project. The Archer project has been accessed by student at several universities and has accumulated over 150,000 CPU hours in a little more than a year. In addition, the Grid Appliance has been used as both a teaching tool in distributed computing classrooms as well as by external users to create their own grids.

CHAPTER 1
INTRODUCTION

A Virtual Private Network (VPN) provides the illusion of a local area network (LAN) spanning a wide area network (WAN) infrastructure by creating encrypted and authenticated, secure[1] communication links amongst participants. Common uses of VPNs include secure access to enterprise network resources from remote/insecure locations, connecting distributed resources from multiple sites, and establishing virtual LANs for multiplayer video games over the Internet. VPNs, in the context of this proposal, differ from others that provide "'emulation of a private Wide Area Network (WAN) facility using IP facilities' (including the public Internet or private IP backbones)." [39]. These style of VPNs connect large sets of machines through virtual routers to a virtual WAN environment.

As a tool enabling collaborative environments, VPNs can be useful for many different types of users. If friends and family require computer assistance and their computer guru no longer lives nearby, a VPN enables access to the emote machine despite networking constraints so long as the user has an Internet connection. When traveling abroad, a user may wish that their Internet traffic be kept private from the local network, a VPN can be used to route all Internet packets through the users home network, ensuring the user's privacy. Older computer and video games have multiplayer networking components that require direct connectivity and even modern games with centralized gaming components stop being supported, players of these games can continue playing with their remote friends through VPNs. Small and medium businesses may find VPNs useful for connecting desktops and servers across distributed sites securing traffic to enterprised networked resources. independent organizations that

[1] For the remainder of this proposal, unless explicitly stated otherwise, security implies encryption and authentication.

each have their few of their own or no resources can combine together their resources through a VPN to create a powerful computing grid.

There are various VPN architecture that attempt to deal with the challenges presented in these use cases. In some cases one VPN approach may work, where another is not applicable, and in some no current VPN approach is applicable. In general VPNs face the following challenges:

- **Configuration**: Initial setup of the VPN. Where will VPN resources be located, what type of security credentials will be used, what are the network parameters, how will users connect to the VPN.
- **Management**: As peers and external resources desire to join the system, security credentials need to be provided to both. External resources need to be linked to the rest of the system. Occasionally peers misbehave, in these situations, peers must have their membership revoked.
- **Connectivity**: Peers may want to connect to a remote environment or to each other. Communicating through a central resource may create bottlenecks, but doing so directly may be impossible due to restrictive network environments.
- **Privacy**: When using a VPN, peers assume that their communication is private. VPNs that establish their links through a centralized system are susceptible to man-in-the-middle attacks, though setting up decentralized systems can be significantly more complicated.
- **Permissions**: Users must be administrators or given the ability to run a VPN by an administrator. Strict environments such as computing labs, novice users, or where existing VPNs run may prevent the user from being able to use their own VPN.

The key to using a VPN in collaborative environments is making it user-friendly and scalable. Applying these requisites to the challenges: a collaborative VPN should be easy to configure, users need not be experts in operating systems (OSs) or networks; a VPN should not rely on any one site or institution to provide connectivity for the entire VPN; adding new users and resources should be straight-forward using approaches familiar to common users; peers should be able to connect to each other directly if and when possible; not only should the communication in the system be secure but the system providing the VPN should be secure; and users should be able to connect to

the VPN so long as there is Internet connectivity. While existing VPN are able to meet some of these requirements, they are unable to meet them all. Centralized approaches (e.g. OpenVPN [92]) by their very nature require dedicated infrastructures and do not allow direct communication between peers though are the only VPN approach to full tunnel operation and guarantee all-to-all communication regardless NAT and firewall conditions. P2P-based approaches (e.g. Hamachi [59], Wippien [67], Gbridge [58], PVC [74]) are vulnerable to man-in-the-middle attacks if session management is handled by an external provider, rely on a central resource for the creation of VPN links, and require centralized relays if direct peer communication across NATs and firewalls fails. Decentralized approaches require manual configuration of links between members of the virtual network (e.g., ViNe [87], Violin [46], VNET [85], tinc [81]). Existing P2P approaches lack scalability (N2N [25] and P2PVPN [38]) or are difficult to configure and lack privacy (I3 [83]).

The focus of this proposal is in VPNs useful for collaborative environments through a novel peer-to-peer (P2P) VPN systems. In this proposal, I will review the key components of a VPN and either show how existing P2P systems can be used to support the components or design and implement new features and systems as necessary. P2P systems align well with collaborative environments in large part due to their decentralized and distributed nature, the challenge in using P2P is ensuring security and scalability. P2P systems can be used to implement scalable autonomic and decentralized systems, though when used in public environments they do not provide very secure environments as they are easily compromised by malicious users, but the cost of hosting a private overlay can out weigh the advantages in collaborative environments. I extend my work from approaches that use P2P to implement scalable virtual networks, IPOP [35] and I3 [83], finishing the work of my predecessors by designing and implementing a system that provides privacy or

user-friendly configurability. At the heart of my contribution are methods enabling secure P2P systems and self-configuring collaborative P2P systems and VPNs.

1.1 Virtual Private Network Basics

VPNs consist of two components: clients that communicate with each other and servers or overlays that provide the infrastructure for clients to find and establish communication with each other. From a users perspective the environment provided by a VPN client is the same regardless of how the server or overlay is implemented. The clients interface with the server can also be abstracted such that clients are quite generic.

In Figure 1-1, we abstract the common features of all VPNs clients, a service that communicates with the VPN system and a virtual network (VN) device for host integration. During initialization, the VPN services authenticates with the system [2] , optionally, querying for information about the network, such as network address space, address allocations, and domain name service (DNS) servers. At which point, the VPN enables secure communication amongst participants.

Clients can authenticate with the overlay using a variety of methods. A system can be setup quickly by using no authentication or a shared secret such as a key or a password. Using accounts and passwords with or without a shared secret provides individualized authentication, allowing an administrator to block all users if the shared secret is compromised or individual users who act maliciously. In the most secure approaches, each client has a unique signed certificate making brute force attacks very difficults. The trade-offs in the approaches come in terms of security, usability, and management. While the use of signed certificates provides better security than shared secrets, certificates require more configuration and maintenance. In a system

[2] A system in this context refers any portion of the VPN system including a central server, another VPN client, or a relay.

comprising of non-experts, the usual setup uses a shared secret and individual user accounts. The secret is packaged with the VPN application, which is distributed through secure channels such as authenticated HTTPS.

A VN device allows applications to communicate transparently over the VPN. The VN device provides mechanisms for injecting incoming packets into and retrieving outgoing packets from the networking stack, enabling the use of common network APIs such as Berkeley Sockets, thereby allowing existing application to work over the VPN without modification. While there are many different types of VN devices, we focus on TAP [54] due to its open source and pervasive nature. TAP allows the creation of one or more Virtual Ethernet and / or IP devices and is available for almost all modern operating systems including Windows, Linux, Mac OS/X, BSD, and Solaris. A TAP device presents itself as a character device providing read and write operations. Incoming packets from the VPN are written to the TAP device and the networking stack in the OS delivers the packet to the appropriate socket. Outgoing packets from local sockets are read from the TAP device.

VN devices can be configured manually though command-line tools or OS' APIs or dynamically by the universally supported dynamic host configuration process (DHCP) [11, 29]. Upon the VN device obtaining an IP address, the system adds a new rule to the routing table that directs all packets sent to the VPN address space to be directed to the VN device. Packets read from the TAP device are encrypted and sent to the overlay via the VPN client. The overlay delivers the packet to another client or a server with a VN stack enabled. Received packets are decrypted, verified for authenticity, and then written to the VN device. In most cases, the IP layer header remains unchanged, while VPN configuration determines how the Ethernet header is handled.

1.2 Computer Network Architectures

All models for computer communication in distributed systems fall under two categories: centralized and decentralized, though they can be further divided to allow for self-configuring dynamic systems through the use of P2P communication. The architectures commonly used for implementing VPN systems are:

- **Centralized Organization and Communication** - These are client server systems, where all distributed peers both locally and remote are clients connecting into a dedicated server resources. Clients never communicate with each other directly only, but rather every message between two clients must traverse the server. Most online social networks (OSNs) are representative of these type of systems, users of OSNs like Facebook [7] and MySpace [8] communicate through centralized environments never directly to each other's computer. The issue with these systems is the reliance on dedicated resources requiring that the server be online for clients to organize and communicate with each other, thus if a server goes offline or becomes overwhelmed by clients the system is rendered useless.

- **Centralized Organization and Decentralized Communication** - The first set of P2P popular P2P systems like the original Napster and Kazaa used this sort of system. Like the client-server model, clients connect to a server to find other clients, though instead of communicating through the server, the clients form direct connections with each other. These approaches are limited by network address translation (NAT) and firewalls that may prevent peers from communicating with each other. In these cases though, the central server may act as a relay allowing the two clients to communicate through it. Unlike systems using centralized communication, these systems are less susceptible to being overwhelmed by client traffic and even if the server goes offline existing client links remain active though new connections cannot be formed.

- **Decentralized with Manual Organization** - To address the issues of a central system going offline, many distributed servers may be used and clients can be configured to connect to any number of them creating an overlay. In these systems, servers are explicitly configured to communicate with other remote and local servers. Though this approach improves upon the issues inherent with completely centralized architectures, if a site goes offline any systems communicating through it will no longer be connected to the rest of the system until the administrator creates additional links or the site becomes active again. Clients in these systems do not typically form direct links with each other, rather they route packets through the overlay. This approach has been used to create scalable VPNs, like ViNe [87], VNET [85], Violin [46], and Layer 2 Tunneling Protcol based VPNs [86].

- **Decentralized with Automatic Organization** - The last model falls under systems that self-organize. In this environment, there is no distinction amongst peers as they act as both client and servers, i.e., a P2P system or overlay. P2P systems are usually distributed with list of common peers. When attempting to connect with the P2P overlay, a peer randomly selects peers on this list until it is able to connect with one. This connection is then used to form connections with other peers currently in the overlay. The overlay can be organized in two different forms: randomly or deterministically creating unstructured or structured overlays, respectively. In an unstructed overlay, links are formed arbitrarily, thus a peer searches for another peer by broadcasting the message or using stochastic techniques. Structured overlays are organized into deterministic shapes, each peer is expected to have connections to certain other peers forming shapes such as rings and hypercubes. Peers can be found deterministically using greedy routing approaches in usually $O(\log(N))$ time. Gnutella [75] file sharing system and Skype [56] are popular examples of unstructured systems, while P2PSIP [1] and distributed hash tables (DHTs) [84] are popular in structures systems. The challenges to unstructured systems is finding data objects in reasonable amount of time, while structured systems suffer when large amount of peers join or leave the system, churn. In general, both approaches are difficult to secure due to their typical application. When used in closed environments though, they have been shown to be very useful, exemplified by Dynamo [24] or BigTable [21].

As this proposal will use structured overlays as the foundation in building scalable, decentralized VPNs, Chapter 2 provides more detailed review of structured overlays and challenges in decentralized communication with emphasis on security, establishing connections, and reliability. I also provide solution to these challenges in the form of private virtual overlays bootstrapping secure overlays using public free-to-join overlays, a decentralized relay system when direct NAT or firewall traversal fails, and an overlay-aware TCP enabling reliable and efficient communication over unreliable links.

1.3 Contributions

In the introduction, I presented a list of challenges a VPNs face. When applied to collaborative environments, the resulting requirements are self-configuring environments enabling even non-experts to setup, deploy, and manage their own VPNs; peers should communicate with each other directly when possible though still have reasonably efficient alternatives; the system should be reliable and ensure the privacy of its users; and users should be able to access the VPN regardless of their access rights. To

address these requirements, I propose a novel GroupVPN using structured overlays consisting of the following novel contributions:

- **Decentralized Relays**: In collaborative environments, most peers will be behind NATs and potentially firewalls as well. While in general 90% of NATs are traversable through existing approaches, not all are and firewalls complicate the matter. While these peers can communicate through the overlay, as the overlay grows, this latency can grow taking seconds for peers to send a message to each other. To improve this situation, I propose the creation of autonomic tw-hop relays between the peers.

- **Private Virtual Overlays**: At any given time, peers may or may not be connected to the overlay. Private overlays can consist of varying sizes of users, in environment where there are very few users, it is possible that ot a single user can provide a dedicated, publicly addressable resource. In this case, the overlay can experience downtimes, even though there may be users behind NATs and firewalls wanting to use the overlay. To address this issue, I propose the use of a public free-to-join overlay to bootstrap into a private overlay. Peers use the public overlay to find each other and exchange connection information using secure messages. Only peers with appropriate security credentials are able to join the private overlay.

- **Overlay Communication Models**: In my experience, when using the overlay based connections, performance suffers due to being processed by the overlay's state machine. To address this issue, I will present three different models for using overlays to establish direct communication: communicating through the overlays state machine, bypassing the overlays state machine but reusing its connection management, and creating links unused by the overlay.

- **Overlay-Aware TCP**: Overlays consist of peers connecting and disconnecting at random and in order to provide light-weight approaches that provide reasonable NAT and firewall traversal are connected using UDP. As such large streams of data cannot be sent reliably through the overlay. This is not an issue when a VPN has administrator permission enabling the reuse of the OS' network stack including TCP, though those that do not need an alternative. To address this issue, I will propose a TCP stack with focus on efficient and reliable streaming using overlays.

- **Self-Configuring VPN Architectures**: Many existing VPN approaches require the users to setup their environment and do not provide a plug and play system. In addition, different environments call for different types of VPNs, explicitly, users need their own VPN instances and clusters may benefit from a single VPN instance for the cluster or may desire fault tolerance of having many but do not want the communication overhead when talking to VPN peers on the LAN. I address this issue with a self-configuring VPN approach that can be applied to various environments scaling from a single computer to many.

- **Userspace Virtual Networking Stack**: To address the case where users do not have permissions to run VPNs, I plan on designing and implementing a VPN requires no user permissions and can connect to other VPNs that do.
- **P2P Enabled Full Tunnel VPN Mode**: When in insecure environments such as browsing private information in a coffee shop, users may desire to prevent local users and administrators from sniffing their traffic. Traditional VPNs support this behavior, but the approach is difficult to implement in P2P systems due to their dynamic nature. All existing decentralized VPN approaches lack the ability to perform this behavior. I propose a method that not only works for decentralized and P2P systems and ensures a greater level of security than that provided by existing approaches in centralized systems.

To supplement this work, I plan on the investigating the application of these systems in the realms of online social networking and grid computing. I will determine feasibility of implementing an online social network using the structured overlays with particular focus on the use of private virtual overlays as social network profiles or profile overlays. In addition, the primary motivation for my work has been the use of self-configuring VPNs and systems for grid computing. In this proposal, my culminating work, I will describe how this system can be used to create a novel self-configuring grid system that allows users who have limited knowledge of operating systems, networks, and computers to create their own grids in a matter minutes.

The rest of this proposal is organized as follows. In Chapter 2, I present an indepth analysis of structured overlays including a review of NAT constraints and traversal and then explore the use of decentralized relays. This leads into Chapter **??** that seeks to understand the performance constraints when using an overlay for direct communication and Chapter **??**, where I will discuss about the security issues in structured overlays and present my private virtual overlays along with the social profile overlays. Chapter 4 continues the discussion of VPNs with focus on the different architectures and how I have implemented one with existing structured overlays and the new components discussed in this paper. The work on overlay-aware TCP and userspace virtual networking stacks are described in Chapter **??**. Chapter **??** details the

construction of grid systems using self-configuring approaches enabled by virtualization.

Finally, I conclude the paper discussing real systems and future work in Chapter **??**.

1.4 Figures and Tables

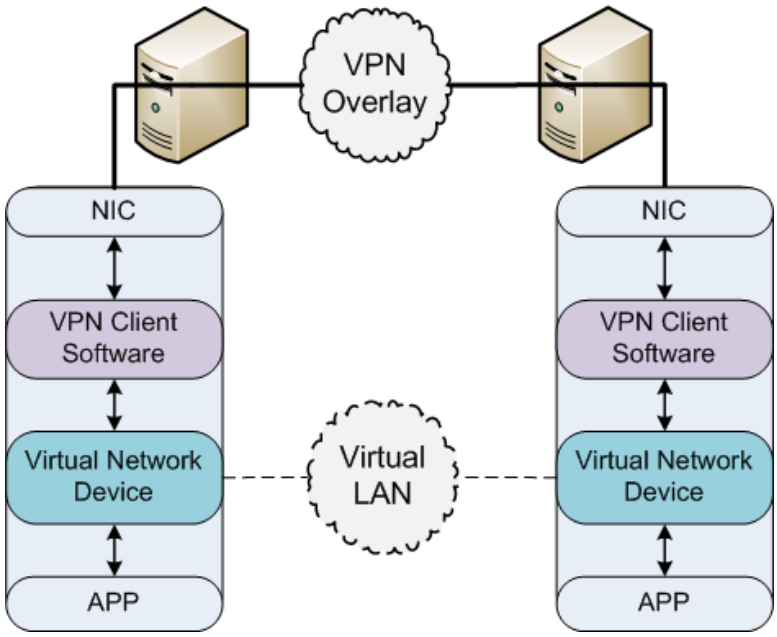


Figure 1-1. A typical VPN client. A VN device makes application interaction with the VPN transparent. Packets going to the VPN destination are sent by routing rules to the VN device interfaced by the VPN client. The VPN client sends and receives packets from other VPN participants via the hosts physical network device.

CHAPTER 2
STRUCTURED PEER-TO-PEER OVERLAYS

Structured P2P systems provide distributed look up services with guaranteed search time with a lower bound of $O(\log N)$, in contrast to unstructured systems, which rely on global knowledge/broadcasts, or stochastic techniques such as random walks [18]. Some examples of structured systems can be found in [13, 62, 63, 71, 79, 84]. In general, structured systems are able to make these guarantees by self-organizing a structured topology, such as a 2D ring (pictured in Figure 2-1 or a hypercube. Joining an overlay usually follows some form of these abstracted steps:

1. generate or obtain a unique identification number (node ID) on the order of 128-bits to 256-bits,
2. connect to random addresses on a pre-shared well-known endpoints list,
3. becomes connected to at least one peer in the list (leaf connection),
4. find the peers closest in the address space to the selected node ID,
5. connect to nodes whose IDs are immediately smaller and / or larger than its (neighbor connections),
6. and finally connect to other nodes in the overlay that are not local in the address space (shortcut connections).

Each node must have a unique node ID, address collisions can prevent nodes from participating in the overlay and can potentially fragment overlays preventing them from working properly. Having node IDs well distributed assists in providing better scalability in structured overlays routing enabling fewer shortcut connections due to the uniformly distributed nature of the system. Each node can generate their own address if they use a cryptographically strong random number generator. Another approach for distributing node IDs relies using a trusted third party to generate node IDs and cryptographically sign them [19].

Depending on the protocol, a node must be connected to closest neighbors in the node ID address space; optimizations for fault tolerance suggest that for ring

topologies the amount should be between 2 to $\log(N)$ on both sides. In the case of overlay disconnectivity especially when related to churn, when a peer does not know the address of its immediate predecessor or successor and a message is routed through it destined for them, depending on the message type, it may either be locally consumed or thrown away, never arriving at its intended destination. Having multiple neighbors assists in stabilizing the overlay structure when experiencing churn, particularly when peers leave suddenly without warning.

Overlay shortcuts enable efficient routing in ring-structured P2P systems. The different shortcut selection methods include: maintaining large tables without using connections and only verifying usability when routing messages [63, 79], maintaining a connection with a peer every set distance in the P2P address space [84], or using locations drawn from a harmonic distribution in the node address space [62].

Most structured P2P overlays support decentralized storage/look-up of information by mapping keys to specific node IDs in an overlay. At a minimum, the data is stored at the node ID either smaller or larger to the data's node ID and for fault tolerance the data can be stored at other nodes. This sort of mapping and data storage is called a distributed hash table (DHT). DHTs provide the building blocks to form more complex distributed data stores as presented in Past [78] and Kosha [16].

There are two mechanisms for message routing in a P2P overlay: iterative or recursive. In iterative routing, the sender of a packet will directly contact each successive member in a path querying it for the next until arriving at the destination node, sending the packet directly to the destination. In recursive routing, messages are sent through the overlay via forwarding from one peer to the next until arriving at the destination. In general, iterative routing is easier to implement though comes with considerable overhead as each overlay query will cause $\log(N)$ connections to form and makes NAT traversal complicated as it will require constant traversal mediation and

need to be made quickly, whereas recursive routing provides stable connections due to a single NAT traversal during the connection phase.

2.1 Network Address Translation Hampering P2P Systems

As of 2009, the majority of the Internet is connected via Internet Protocol (IP) version 4. A limitation in this protocol is that there are only 2^{32} addresses total though or approximately 4 billion addresses. With the Earth already having a population of over 8 billion and each individual having multiple devices that have Internet connectivity the IPv4 limitation is becoming more and more apparent. IPv6 provides an alternative, supporting 2^{128} addresses, it is not pervasive with only X% of the Internet reachable via IPv6. In the meantime during the transition from IPv4 to IPv6, network address translation (NAT) enables many machines and devices to share a single IP address. The cost of this operation means that such machines lose direct addressability on the Internet.

When a machine, *A*, behind a typical NAT, *B*, sends out a packet to an Internet host, *C*, the NAT box translates the packet so that it appears it is coming from the NAT device making the NAT box a gateway. When the the packet is sent from *A* to *C*, the source and destination are listed as IP, port pairs, where the source and destination are $IP_A : Port_A$ and $IP_C : Port_C$, respectively. *A* forwards the packet to *B* who transforms the source from $IP_A : Port_A$ to $IP_B : Port_B$, where $Port_A$ may or may not be equal to $Port_B$. This creates a NAT mapping so that incoming packets from $IP_C : Port_C$ to $IP_B : Port_B$ are translated and forwarded to $IP_A : Port_A$.

There are a handful of recognized NAT devices as presented in [77, 82]. The following list focuses on the more prevalent types:

- full cone - all requests from the same internal IP and port are mapped to a static external IP and port, thus any external host can communicate with the internal host once a mapping has been made,
- restricted cone - like a full cone but requires that the internal host has sent a message to the external host before the NAT will pass the packets,

- port restricted cone - like a restricted cone but requires that the internal host has sent the packet to the external hosts specific port before the NAT will pass packets,
- symmetric - each source and destination pair have no relation, thus only a machine receiving a message from an internal host can send a message back.

Peers on cone NATs can easily be traversed so long as a third party assists in determining the port allocated by the NAT and they exchange NAT penetration messages. Peers behind symmetric NATs cannot easily communicate with each other, since there is no relation between remote hosts and ports and local ports. Further complicating the matter is that there are various types of symmetric NATs, having behaviors similar to full, restricted, and port restricted cone NATs. [2] describes methods to traverse these NATs so long as there is a predictable pattern to port selection. In general, these approaches use UDP because of the lack of additional protocol states, that require replay and ignoring reject methods that occur with the TCP handshake, though there is reasonable amount of work describing TCP NAT traversal such as [41]. TCP NAT traversal is complicated by stateful firewalls, or those that watch connections and connection attempts preventing messages from closed TCP channels from passing through the NAT. For NAT situations that cannont be traversed, a third party can act as a relay between the two, this is known as triangulation or traversal using relay NAT (TURN), described in [76].

2.1.1 NAT Traversal in Structured Overlays

Structured overlays rely on the principle that any peer can become directly connected with any other peer in the system. Thus in order to use structured overlays on the Internet, they must either be run on publicly accessable addresses or support NAT traversal. Even in the case where there is NAT traversal, occassionally there are Internet routing table breaks and two peers who should be able to directly communicate cannot.

To date, there exists only one solution, Brunet [13], supporting decentralized UDP NAT traversal and limited relays. To support UDP NAT traversal, Brunet makes connection attempts bidirectional with peers exchange all known IP addresses and

ports, which it knows directly and from external overlay nodes. This enables the traversal of all forms of cone NATs, but symmetric NATs require iterative rounds of traversal attempts and cannot be traversed. If two peers cannot connect, they exchange list of peers, if an overlap exists, they will forward packets through it to each other [33], this approach was used to ensure the structure of the overlay and cannot be used to form arbitrary relay connections. To address this as my interest lie in forming efficient VPNs, I have designed a technique that causes peers to proactively creates overlap and when multiple overlap exist to route through the most attractive candidate, as represeted in Figure 2-2.

To assist in the selection of overlap connection, peers exchange arbitrary information along with the neighbor lists. So far I have implemented systems that share information about node stability (measured by the age of a connection) and proximity (based upon ping latency to neighbors). When overlap changes, peers can select to use only a subset of the overlap, thus only the fastest or most stable peers are used with extras in reserve.

2.1.2 Usefulness of Relays

To verify the usefulness of two-hop over overlay routing, I have evaluted the latency approach using an event-driven simulator that reuses the code base of IPOP to faithfully implement its functionality using event-driven simulated times to emulate WAN latencies. For this experiment, I chose latencies based upon the MIT King Data Set [42], which consists of all-to-all latencies between 1,740 well-distributed Internet hosts. We then evaluated overlays using various network sizes up to 1,740. After starting the overlay and the system reaches steady state, that is the overlay is completely formed and no new connections are created, I measured the average all-to-all latency for all messages that would have taken two overlay hops or more, the average of the low latency relay model, and the average of single hop communication. In the low latency relay model, each destination node form a connection to the source node's physically closest peer

as determined via latency (in a live system by application level ping). Then this pathway is used as a two-hop relay between source and node. We only look at two overlay hops and more, as a single hop would only benefit under triangular inequalities that are not a consideration in my work.

The results are presented in Figure 2-3. I performed the tests for varying network sizes. Tests began with network sizes of 25, sizes around 20 and under tend to be fully connected due to the connectivity requirements of the system. It is not until the network size expands past 100 and towards 200 nodes that relays become significantly beneficial. At 100 nodes, there is approximately a 54% performance increase, whereas at 200 there is an 87% increase and it appears to grow proportionately to the size of the pool. The key take away is that latency-bound applications using a reasonably sized overlay would significantly benefit from the use of two-hop relays.

2.2 Using Structured Overlays for Direct Communication

Applications like VPNs, games, media, and communication can benefit from using an overlay for discovery and limited communication, though as communication increases in frequency direct communication may be perferred. In previous work [36], the authors describe a method for transparently detecting this behavior and creating direct links as a result. In comparing a VPN built on top of an overlay with a point-to-point direct approach, the VPN using the overlay has significant overheads due to each IP packet traversing the overlays state machine prior to being sent to the VPN. Thus for high bandwidth applications, this approach does not scale and costs significant CPU utilization.

To address this issue, I propose two models in addition to the existing approach to using an overlay for high bandwidth purposes. These two approaches are: 1) use the structured overlay to create and maintain links but placing the application between the connection and the overlay stack so that the application has first access to the data and 2) use the structured overlay to discover peers but the application creates and manages

its own links using the structured overlay to coordinate these efforts. The proposed approaches are presented in Figure 2-4.

The first approach benefits from using existing components of the structured overlay including link creation and maintenance though may still have overheads due to packets needing to traverse both the application and overlays stack. This can be addressed by creating a unique thread for processing packets in the application as well as the overlay stacks. Since the connections are shared, this approach will require additional thread sychronization.

The second approach is more complex but both components reside in completely different memory spaces. The application might be easily coded through code reuse, but this still significantly increases the complexity of the solutions. Because the stacks each component has its own stack, there is no need to handle synchronization. The VPN will have unfettered access to the connections it has established.

2.3 Overlay-Aware TCP

When sending a message via an overlay, if a packet is lost in transit, there are no built-in methods for recovering the transmission, the overlay acts like a datagram system. Even when links are connected by TCP, a disconnectivity or failure in the overlay will not trigger successful TCP transmissions to transmit the packet to another host. When using UDP, there are no built-in methods. Current approaches either fail or attempt a simple retry mechanism. Even in the case of retrying, UDP does not handle fragmentation well and to support retrying either requires complicated state to handle large packets or a simple state that cannot support large packets. I implement an overlay TCP system and use it in real system to determine other challenges that exist when using it.

2.4 Figures and Tables

Figure 2-1. 1-D Ring Structured Overlay

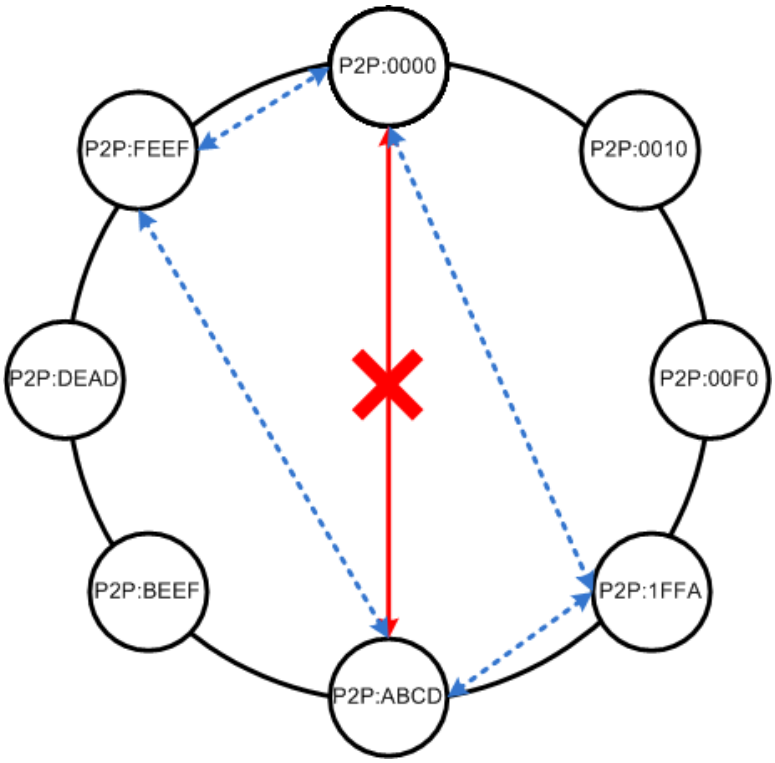


Figure 2-2. Creating relays across the node address space, when direct connectivity is not possible. Two members, 0000 and ABCD, desire a direct connection but are unable to directly connect, perhaps due to NATs or firewalls. They exchange neighbor information through the overlay and connect to one of each other's neighbors, creating an overlap. The overlap then becomes a relay path (represented by dashed lines), improving performance over routing across the entire overlay.

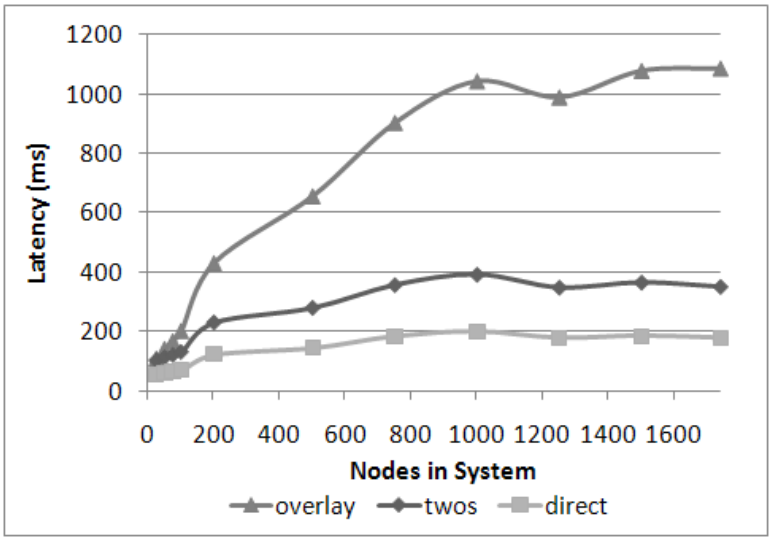


Figure 2-3. A comparison of the average all-to-all overlay routing, two-hop relay, and direct connection latency in a Structured P2P environment, Brunet, using the King data set.

Figure 2-4. Direct communication models

CHAPTER 3
VIRTUAL PRIVATE OVERLAYS

While Structured P2P overlays provide a scalable, resilient, and self-managing platform for distributed applications, though their adoption rate has been slow outside data distribution services such as BitTorrent and eDonkey. General use of structured P2P systems, especially in applications targeting homes and small/medium businesses (SMBs), has been limited in large part due to the difficult nature of securing such systems to the level required by these users. Applications in home and SMBs may need a greater level of trust than what can be guaranteed by anonymous contributors in free-to-join overlays, but these users lack the resources for bootstrapping private P2P overlays particularly in constrained wide-area network environments where a significant amount of or all peers are behind Network Address Translation devices (NAT).

There are many different P2P applications used in home and small business, primarily for collaboration and sharing, including data storage, media sharing, chat, and system maintenance and monitoring. Applications that currently provide these functionalities fall into two categories: anonymous, fully decentralized free-to-join P2P systems and distributed systems with P2P communication that rely on a third party to provide discovery and management. While using a third party service provides a desirable level of trust for many users, it has significant drawbacks such as vendor lock-in, which may result in lost data, down time, and scalability constraints.

An example of a useful small business application that falls into the latter category is LogMeIn's [60] software products LogMeIn Pro and Hamachi. LogMeIn Pro allows users to remotely manage and connect with their machines so long as they are willing to use LogMeIn's software and infrastructure. Hamachi allows users to establish decentralized VPN links using centralized session management. Both applications assist in the remote maintenance and monitoring of computers without requiring the user to implement the networking infrastructure provided by LogMeIn.

Some examples of P2P applications for homes and small businesses in development are P2PSIP [1] and P2Pns [3]. P2PSIP enables users to initiate, through decentralized means, visual and audio communication, while P2Pns allows users to deploy a decentralized naming service. Both applications allow users to contribute and benefit from all members of the system without the regulation of a third party, but lack the ability to allow users to centrally secure and manage their own subset of the systems.

Distributed data store applications like Dynamo [24] and BigTable [21] have the ability to store data using a completely decentralized system. Though these systems are highly scalable and fault tolerant, the software uses an untrusted overlay. Therefore all instances need to run in a secure environment, whether that is in a single institution or across a largely distributed environment using a VPN.

This chapter reviews security issues and current examples of security in P2P. Using the motivation of user centric and friendly systems, I present a method for users to create their own secure, private overlays using the same core overlay primitives as public overlays without the constraints imposed on them by lacking dedicated, public resources through the use of a shared, free-to-join public overlay.

3.1 Security Issues in Structured Overlays

While there has been much research [19] in securing overlays through decentralized mechanisms that attempt to prevent collusion known as a Sybil attack [28], these mechanisms do not create private overlays. One approach mentioned does provide a natural lead into such environments by using of a pay-to-use service to mitigate the chances of an overlay attack, whereby the pay to use service uses a CA to sign node IDs. The work does not describe how to efficiently implement such a system. Other projects [27, 45] combine trusted overlays with anonymous members, though it could be reasonably argued these services are not applicable to small or medium business, which would prefer to have a private overlay. None of the works focus on how to apply such models to systems that are constrained in network connectivity, e.g. by NATs.

3.2 Secure Overlays

In recursive overlays There are two forms of overlay communication:

- **Point-to-point (PtP)**: Direct connections between peers in an overlay, such as a UDP, TCP, or relay connecting two peers. In an iterative system, all messages are PtP.
- **End-to-end (EtE)**: Messages passed through an overlay from peer to peer, used typically for application communication such as DHT queries.

Iterative overlays do not distinguish between the two forms of communication as all communication is directly between two peers and never indirectly communicated unless relays are used.

Securing communication in overlays using iterative routing without relays and static IP addresses can easily be done using TLS [26] or DTLS [73] with certificates bound to the node's IP address. Similarly PtP can be secured in recursive overlays with static address. Including relays, NAT traversal, or EtE in recursive overlays complicates the issue. NAT traversal cannot must bind the certificate to something other than the peers IP address. Relays and EtE routing require communicating through indirect communication and existing security libraries are built on top of sockets and thus are not applicable in these environments. Furthermore, overlays are not reliable environments and thus without a reliable overlay primitive TLS cannot be employed. DTLS can be applied because it supports lost and out of order messages, though the implementation must support usage without a socket. In this section, I discuss how to bind security protocols and a certificate model to an overlay system addressing the issue of applying DTLS to overlays and binding certificates to individuals even in NAT environments.

The key to my approach is the abstraction used in the communication layer, making EtE and PtP traffic appear identical. In this approach, all messages are treated as datagrams, which are sent over abstracted senders and receivers as filters illustrated in Figure 3-1. This allows use of secure tunnels over these links with no application changes.

Exchanged certificates need a mechanism to verify authenticity. Like an Internet browser, this verification should happen automatically with no user intervention. Typically for SSL-derivatives, the certificates have the owner's IP address or domain name as part of the certificate's common name field. In our system, we bind the certificate to each individual node ID. That way, a single certificate cannot be used for multiple peers in the overlay, making it difficult for an adversary to launch Sybil attacks.

3.2.1 Forming the Connection

In overlay systems, a peer's connection manager requests an outgoing connection to another peer in the system. This triggers the creation of a socket (UDP or TCP), which is wrapped in the abstracted sender and receiver models. The abstracted models arrive into the security handler, which authenticates in both directions and creates a secure session. The session is wrapped in the same abstracted model and presented to the overlay system as a direct connection to the remote peer. To keep the system abstract, the security model and the wrapped sockets know nothing about the overlay, and so the overlay should verify the certificate to ensure identity.

Because EtE communication is application-specific, it requires a slightly different path. For that purpose, users can obtain a secure EtE sender through an instance factory, allowing multiplexing of secure senders for multiple applications as well as PtP communication. Once an application requests the sender, the module passes a sender / receiver model to the security handler, like in the PtP process. Once the security initialization has completed, the resulting sender / receiver is verified automatically for proper identity. If that succeeds, messages sent using the EtE sender will arrive at the remote party, decrypted and authenticated by the security handler, and delivered to the overlay application, who will deliver to the remote party's handler for such messages. Since overlay applications will be sending and receiving unencrypted as well as encrypted EtE traffic, the handler must verify that the packet was sent from a secure end point. This assumes that an application using an overlay has already implemented

verification of node ID to some application mapping. For example, an application could be aware that node ID X maps to user Y, therefore if a secure message coming from node ID Z says that it is user Y, an application should drop the packet.

3.2.2 Datagram Constraints

Since UDP is connectionless, applications that use it can easily be victims of denial of service attacks. This is because packets sent to the receiver can have a spoofed source address, unless the outgoing gateway prevents this from occurring, egress filtering. For each spoofed attempt, the security system will maintain state, which can eventually be overloaded. In TCP, this is hampered due to the three message handshake, which verifies that a source address is not spoofed, prior to creating security state for the connection. To reduce the potential of these spoofing attacks prior to establishing a secure connection, DTLS (like Photuris [50]) uses a stateless cookie for each remote peer. In DTLS, the cookie is usually based upon the remote peer's IP and the current time. In our model, which deals with abstracted systems and IP addresses are likely to be NAT-translated, this approach does not work. Though for PtP, it is possible to use the address and port from which the remote peer last sent a message from. For EtE traffic, the node ID can be used for cookie calculation. Because we are building on existing senders and receivers that already have state, we use the object's memory pointer or hash value instead, though this leads us down a similar path of denial of service found in TCP SYN attacks.

3.2.3 Implementation

To provide security, I investigated two approaches: reusing OpenSSL's DTLS implementation and a own platform-independent DTLS using C# using cryptography routines provided by .NET. A constraint in the development is that EtE communication must be able to be secured, which could be enabled by a filter approach using memory buffers instead of sockets.

Implementation of an OpenSSL DTLS filter was non-trivial, as documentation is sparse providing the possibility for varied approaches. Traditionally, DTLS uses the DGRAM (datagram) BIO (I/O abstraction) layer, which provides a reliable UDP layer. Because we need a filter, so that we can do both EtE and PtP traffic, we used one memory BIO for incoming traffic and another for outgoing traffic. Memory BIOs provide pipes using RAM: data written to the BIO can then be read in a first in, first out ordering. Incoming messages written to or outgoing messages read from the DTLS read or write BIOs, respectively, are either encrypted data packets or handshake control messages. Sending and receiving clear text messages occur at the DTLS SSL object layer. The pathway for sending a clear text packet begins with the user performing an SSL_write operation, retrieving the encrypted data by performing a BIO_read on the write BIO, and sending the data over the network. At the remote end, the packet is passed to the SSL state machine by performing a BIO_write on the incoming BIO followed by a SSL_read; the result will be the original clear text message. This process also needs to handle control messages; we provide clear context in Figure 3-2. As an aside, OpenSSL supports a SSL filter BIO, though it will not work for this purpose as BIOs that are inserted are expected to have two pipes, like a socket or two memory buffers. Also the only benefit of using the filter BIO would be that it manages auto-renegotiation, which can be implemented in user code by monitoring time and received byte count. Other operations such as certificate verification and cookie generation are handled by SSL callbacks, which hook into our security framework.

OpenSSL is a de-facto standard, with US federal government approved code and platform portability, though during my development involving the platform I experienced a few issues. The portability provided by OpenSSL is limited to API (Application Programming Interface) and not ABI (Application Binary Interface), which requires a platform-specific library be either installed or distributed with the application. Whereas the purpose in using C#, like Java, is that a single binary can run on any platform. To

use unmanaged libraries from a managed language requires a marshaling wrapper to handle the translation; there is such a wrapper for OpenSSL [55]. A constraint we found when using the library was the naming of the OpenSSL libraries was not consistent across platforms and, additionally, Windows lacked a formal installation method.

In using the OpenSSL library with DTLS, in version 0.9.8k, renegotiation of security parameters was broken and would result in a deadlocked DTLS session, whereas in 1.0.0-beta3 (the latest released beta) DTLS renegotiation worked; however, it would often segmentation fault. These issues were the motivation for the creation of a platform independent security architecture similar to DTLS written in C#. To provide for flexibility between the two approaches, I created a security overlord that treats each approach like a filter. Treating each implementation as a filter allows incoming control and data messages to be pushed into the object and data and control messages to be pulled out of the object. While I believe OpenSSL's DTLS to be a superior choice due to its prevalence and being well studied, it is non-trivial to make available for all platforms. Because my goal is to provide a safe yet easy to use the overlay package, I leave the decision up to the user which protocol to use. I believe those interested in testing the system will start with the .NET security stack and migrate to the OpenSSL DTLS stack.

Since symmetric keys work on limited block size, they use modes of operation to encrypt or decrypt large sets of blocks. Because DTLS uses an unreliable transfer mechanism, each message should be able to be decrypted without the use of previous messages. As suggested in the DTLS paper, we used cipher-block chaning (CBC) with a new initialization vector (IV) for each message. During analysis of our C# implementation, we discovered that generating an IV was expensive but the initialization of an additional CBC state machine was even more. To reduce these costs, the sender always uses the same CBC state machine and prepends the last cipher-block to the beginning of the next message. Upon reception, a receiver compares the prepended message to a cache of CBC state machines stored by the current state, if there is a

match, then the CBC state machine can be used, otherwise, if the packet is received out of order the receiver can start a new CBC state machine to decrypt the packet. Table 3-1 compares the overhead with the default implementation and with our revised version. This issue does not appear in the OpenSSL implementation of CBC.

3.3 Private Overlays

The main components involved in the starting and maintaining a private overlay are 1) dissemination of the security credentials and its name, 2) connecting with and storing data in the public overlay, and 3) discovering and connecting with peers in the private overlay. Step 1) can be application-specific; we propose a generic interface that is useful in many applications, through the use of groups as described in Section Section 3.4. For 2), we presume the usage of a structured overlay as described in Chapter 2. In this section, we discuss 3), the steps involved in creating and connecting to a private overlay after the user has obtained group information and has connected to a public overlay.

To connect with and create a private overlay, the application performs the following steps, as depicted in Figure 3-3: 1) connect to the public overlay; 2) store node ID in the public overlay's DHT at the private group's key; 3) query the public overlay's DHT at the private group's key; 4) start an instance of the private overlay with the well-known end points being the node IDs retrieved from the DHT; and 5) upon forming a link with a member in the private overlay, the node follows the standard approach for linking to neighbors and shortcuts but using secure PtP links to restrict connections to members of the private overlay.

While a node does not need to maintain membership in the public overlay once connected with the private overlay, it will benefit the private overlay for it to do so. If the peer remains in the private overlay, other peers can discover the node while following the same set of steps and, for NAT traversal purposes, as discussed in the next paragraph. Because the public overlay and its DHT provides a means for discovery,

nodes should maintain their node ID in the public overlay's DHT. If the DHT employs a lease or soft state system, while online the node must renew the lease prior to expiring.

During the formation of the private overlay, peers may find that they are unable to form direct connections with other members of the private overlay even while using STUN based NAT traversal. To address this problem, peers can 1) use TURN NAT traversal in the nodes overlay as in Chapter 2 or 2) use the public overlay as an extra routing massive TURN infrastructure. The TURN NAT traversal technique has both peers connect with each other's near neighbors in order to form a 2-hop connection with each other. The 2-hop route can either be enforced through a static route or through EtE greedy routing. Due to the abstractions in the system, the public overlay can be treated as another mechanism to create PtP links, thus while packets may use EtE routing on the public overlay, the private overlay nodes treat it as a PtP connection thus all communication is secured. This approach can be further enhanced by allowing the private overlay to apply the TURN NAT traversal technique to the public overlay. To do this, the private overlay must be capable of requesting a direct connection between its node and the remote peer in the public overlay. This would trigger the eventual creation of a 2-hop relay connection as presented in Figure 3-4.

If overlays are small and have significant churn, it is expected that data stored in the overlay's DHT to be lost. This can be improved by also supporting broadcast in the private overlay. In this model, each peer acts as a storage point for all data critical to itself. If another peer cannot successfully find data stored at a specific key in the overlay, it can make use of broadcast over the entire overlay in an attempt to find the result. The technical details of Brunet's broadcast implementation are described in Appendix 7. As the broadcast involves forwarding packets, the revoked peer will receive a revocation notice but the forwarder does not include it in the calculations of bounds and thus they are never responsible for forwarding the revocation onwards.

During evaluation, I discovered that in certain cases the private overlay would not form a proper well-formed state but rather more than one distinct overlays, creating a partitioned overlay. The underlying issue was that the partitioned overlays believed they were in a well-formed state and thus never reviewed the DHT list to determine if there were peers that should be their neighbors. This caused the overlay to remain fragmented until either a new peer joined or enough peers left causing the nodes to believe they are in a non-well-formed state and require bootstrapping links. The issue stemmed from significant churn, especially during bootstrapping of significant new nodes in the public overlay, causing entries in the DHT list can become partitioned, with each set of nodes potentially seeing different lists. Eventually the lists stored in the DHT become consistent, but at that point, the overlay would have already been partitioned.

To proactively solve the partitioning issue, the node performs the following steps: 1) continuously query the DHT; 2) upon receiving the DHT query result, the node determines if there is a peer with whom it should be connected to such as that it is closer in the address space than any of its current neighbors; 3) form a connection with that peer; and 4) the system should automatically at this point in time realize the network fragmentation and heal itself. In our system, this involved creating a bootstrapping connection with the peer. Upon a successful connection, the system automatically causes the networks to heal.

3.4 Group Overlays

Establishing trusted links in a P2P system can easily be achieved via a PKI model, where a centralized CA for a group signs all client certificates and clients can verify each other without CA interaction by using the CA's public certificate. However, setting up, deploying, and then maintaining security credentials can easily become a non-negligible task, especially for non-experts. Most PKI-enabled systems require the use of command-line utilities and setting up your own methods for securely deploying certificates and policing users. While this can be applied to an overlay, my experience

with real deployments indicates that usability is very important, leading us to find a model with easy to user interfaces. A solution to this issue is a partially automated PKI reliant on a redistributable group based web interface. Although this does not preclude other methods of CA interaction, experience has shown that it provides a model that is satisfactory for many use cases.

3.4.1 Joining the Group Overlay

Membership of an overlay maps a set of users as a group, easily enabling PKI models via group infrastructures. Using this system, a user can host an individual or multiple groups per web site. The creator of the group becomes the default administrator, and users can request access to the group. Upon an administrator approving, users are able to download configuration data containing overlay information and a shared key used by the overlay application to communicate securely with the web interface. The shared key uniquely identifies the user to the web site allowing the application to securely send certificate requests. By default, the web site automatically signs all certificate requests, though it is not limited to this model. Two other approaches are 1) require the user to submit a request and wait for an administrator to verify each request and 2) set a maximum amount of automatic request signings then requiring administrative approval for more.

As stated in Section 3.2, the certificate request is bound to the application's node ID, which can be generated by the CA or the application. Additionally in the group system, the certificate also contains the user who made the request and the group for which the certificate is valid. Not only does this ensure that a single certificate can only be used for each node instance, but it reduces the amount of state necessary to revoke a user from a system. Specifically, to revoke a user, the CA would only need to provide a signed revocation notice containing the user's name and not every one of the previously signed certificates.

Upon receiving a signed certificate, the overlay application can connect to the overlay where all PtP traffic will be secured and, optionally, so can EtE traffic. It is imperative that any operations that involve the exchanging of secret information, such as the shared secret, be performed over a secure transport, such as HTTPS, which can be done with no user intervention.

3.4.2 Leaving or Being Removed from a Group

In the group environment, administrators also have the ability to remove users from the group. In turn, this will cause a user revocation, which is detailed more in Section 3.5. In addition, users that leavethe group should also have their certificates revoked, attempting to revoke a user's certificates after they have left the group can be a difficult undertaking if the group interface no longer has memory of those users. Once a user has been revoked, the account should never be unrevoked as ensuring that a user has received a notice to revoke an existing revocation can be difficult to verify in a live system. Instead, revoked or users who have left should be forever listed in the group and if the users are welcome back again, they should create new accounts. Alternatively, unique numbers could be assigned to a user, thus an account number and not a username could be revoked.

3.5 User Revocation

Unlike decentralized systems that use shared secrets, in which the creator of the overlay becomes powerless to control malicious users, a PKI enables the creator to effectively remove malicious users. The methods that we have incorporated include: a user revocation list hosted on the group server, DHT events requesting notification of peer removal from the group, and broadcasting to the entire P2P system the revocation of the peer.

A user revocation list offers an out-of-band distribution mechanism that cannot easily be tampered, whereas communication using the overlay can be hampered by Sybil attacks. The revocation list is maintained on the Web site and updated whenever

an administrator removes a user, or a user leaves the group. Additionally it can be updated periodically so that a user can verify that the revocation list is up to date.

However, because the user revocation list requires centralization, users should not query it prior to every communication nor periodically during conversations. In addition to support for polling the revocation list, the use of the DHT and broadcast provides active notification of user revocation. Revocation through the DHT method allows a peer to request notification if another peer is revoked from the group. To subscribe for this notification, the peer inserts its node ID at the peer's revocation notification key, which we represent as a hash of its node ID. Upon revocation, the CA will first insert a revocation notice at this key and then query the key for all node IDs notifying each of them of the revocation. The insertion of the revocation notice handles a race condition, where a peer may insert its ID but never receive a notification. Thus after inserting the request for notification upon revocation, the peer should ensure that a revocation has not occurred by querying the DHT to verify the non-existence of a CA revocation.

When the group is securing PtP traffic, the DHT approach does not effectively seal the rogue user from the system until all peers have updated the revocation list. A peer may continuously connect to all peers in the system until they have all queried the DHT key prior to verification. Due to this issue, we consider an additional model in the group overlay: an overlay broadcast, ensuring that all peers in the private overlay do know about the revocation.

Because the security framework is based on PKI, another approach that is also supported is the use of certificate revocation lists (CRL) found in most CA systems. The advantage of a CRL and revoking individual certificates is the ability to remove a subset of a user's node, particularly useful in the case that the user was not malicious but that some of their nodes had been tampered or hijacked.

3.6 Applications

This sectoin presents some applications annd potential ways to configure them to use a private overlay. The applications investigated include chat rooms, social networks, VPNs, and multicast. The key to all these applications is that users can easily host their own services and be discovered through the use of a NAT-traversing, structured overlay network.

3.6.1 Chat Rooms

Chat rooms provide a platform for individuals with a common interest to find each other, group discussion, private chat, and data exchange. One of the most popular chat systems for the Internet is Internet Relay Chat (IRC). As described in [65], IRC supports a distributed tree system, where clients connect to a server, and servers use a mixture of unicast and multicast to distribute messages. The issues with IRC are documented by [49], namely, scalability due to all servers needing global knowledge, reliability due to connectivity issues between servers, and lack of privacy. Private overlays could be extended to support the features of IRC and potentially deal with these inherent issues. Each chat room would be mapped to a private overlay and the public overlay would be used as a directory to learn about available chat rooms and request access. Structured overlays do not require global knowledge and can be configured to handle connectivity issues. Additionally, IRC by default uses clear text messaging and even if security is used a server will be aware of the content of the message, two issues resolved by using PtP security in a private overlay chat room.

3.6.2 Social Networks

Social networks such as Facebook and MySpace provide an opportunity for users to indirectly share information with friends, family, and peers via a profile containing personal information, status updates, and pictures. Most social network structures rely on hosted systems, where they become the keepers of user data, which creates privacy and trust concerns. Private overlays can remove this third party, making users the only

owner of their data. For this model, we propose that each user's profile be represented by a private overlay and that each of their friends become members of this overlay. The overlay will consist of a secured DHT, where only writes made by the overlay owner are valid and only members of the overlay have access to the content stored in it. In addition to bootstrapping the private overlays, the public overlay would be used as a directory for users to find and befriend each other. For fault tolerance and scalability, each user provides a copy of their profile locally, which will be distributed amongst the private overlay in a read-only DHT, therefore, allowing the user's profile to be visible whether they are offline or online. Each user's social network would than consist of the accumulation of the individual private overlays and the public overlay. This is covered in greater depth in Section **??**.

3.6.3 P2P VPNs

As will be described later in Chapter 4, private overlays enable P2P VPNs. The most common type of VPNs are centralized VPNs like OpenVPN, which requires that a centralized set of resources handle session initialization and communication. Another approach taken by Hamachi and many others is to maintain a central server for session initialization but allow communication to occur directly between peers and providing a central relay when NAT traversal fails. Using a structured private overlay allows users to host their own VPNs, where each VPN end points is responsible for its own session initialization and communication. The private overlay also provides mechanisms for handling failed NAT traversal attempts via relaying.

3.6.4 Multicast

The topic of secure multicast has been a focus of much research. Using an approach similar to CAN [72], a virtual private overlay forms a ring where all nodes are members of the multicast group with the additional feature that you can trust that your audience is limited to those in the overlay. The main advantage of such multicasting technologies would be for wide-area, distributed multicast. Examples of such services

include light weight multicast DNS / DNS-SD (service discovery), as well as audio and video streaming.

3.7 Evaluation of Private Virtual Overlays

In this section, I evaluate the time required to create and join private virtual overlays using a three different environments:

- **Network Modeling**: To model the system, I have implemented an application that generates a structured overlay with the usual dimensions found in deployed steady state systems: a system of size N with each peer having 3 near neighbors on both sides and $O(.5 \log N)$ shortcuts. The modeler creates a fully connected system where shortcuts are optimally chosen based upon their location in the node ID space using a harmonic distribution. Brunet routing code can then be used on a fully generated overlay to model the number of nodes visited and message latencies. Delays between nodes was generated using the MIT King data set [42]. The MIT King data set consists of latency between DNS servers distributed globally on the Internet. Since the MIT King data set only covers 1740 nodes, peers in largers networks are randomly distributed in the address space placing multiple nodes at the same "physical" location when necessary. The overhead due to security was modeled by adding 3 round-trip latencies to prior to all connection processes. This models the behavior of the 6-message DTLS handshake used in the deployed code base.

- **Simulations** The approach described above estimates time based upon a model that reuses the core routing algorithm of the overlay code but does not fully capture the dynamics of the overlay such as state machines involved in connection handling. To allow complete evaluation of our software stack, I have also implemented a simulator using event-driven time that faithfully reusing the entire overlay code base including routing, security, DHT, and connection state machines. This allows the verification of correct behavior in the overlay prior to testing out on real systems, such as PlanetLab, as well as to perform experiments in a controlled environment, which simplifies the evaluation while still retaining the effects of a wide-are distributed system. This environment, like the network modeler, employs the MIT King data set [42] for pair wise latency between peers. Because the network modeler is very light weight, it can model more than 100,000 peers using a single computer; however, the simulator reuses the entire overlay software and can only simulate around 1,000 peers.

- **PlanetLab** PlanetLab [22] is a consortium of research institutes sharing hundreds of globally distributed network and computing resources. PlanetLab provides a very interesting environment as there is constant unexpected churn of machines due to the extreme load placed on the resources and unscheduled system restarts. Complementary to simulation, PlanetLab gives a glimpse of what to expect from

the P2P software stack when used in an actual environment subject to higher variance due to resource contention and churn. Due to the time required and complexities in working with PlanetLab, it is used only for a limited number of experiments with focus on the time required to join a private overlay.

3.7.1 Connecting to the Private Overlay

This experiments provides light on the overall time required for a node to connect to the public overlay, and then for a subsequent paired node to connect to the private overlay. Connected implies that a node has with the nodes whose IDs are closest in the ring (i.e., neighbors with IDs both smaller than and larger than the node who is joining). The results of this experiment show the time it takes to connect to a public overlay, query the DHT for private overlay information, and then connect to a private overlay with and without security.

To summarize the connection process, the public node is started. Upon becoming connected, the private node will insert into the DHT its private overlay information using an automated lease extender. Afterwards, it queries the public overlays DHT for information regarding other nodes. Upon successful retrieval, the results are appended to the list of potential nodes from which the bootstrapping state machine pulls addresses from during the early connection phase. The test terminates when the private node reaches a connected state. The private node is started after the public node due in part to earlier experiments, in which it was noted that starting the public and private nodes at the same time took longer due to the state machines in the private node using exponential time back-offs of up to a minute when there were no nodes in the bootstrapping node list.

For PlanetLab, several overlays with random distribution of private nodes were created. Starting from a base public overlay of 600 nodes on distinct PlanetLab hosts, each node randomly decides whether or not to join the private overlay in order to obtain private overlays consisting of 5 to 600 members. Crawling the overlay provided the actual amount of nodes in the private overlay. The experiment entailed connecting to

the ring from the same physical location 100 times using a different node ID each time, causing the node to join different peers and creating a distribution of connection times. During this process, the time it took for the public node and private nodes to connect is measured. Experiments were started after waiting an hour to ensure the system was fully connected or reached steady state. This is a conservative value; experience suggests that overlays run on PlanetLab with various sizes can form a complete ring in the order of minutes.

Simulation follows similar steps though with the peer count tightened to exact amount of peers in both the public and private overlays. The public pool contains 700 nodes and the private pool 2 to 300 members. After waiting for the overlay to become fully connected and additional 60 simulated minutes is executed to ensure steady state. At which point, an additional public node with a matching private node are added to the system. The results measures are the time required for them to become connected.

The modeler repeats the steps done for the simulation, though with network sizes up to 100,000 nodes. To verify the modeling evaluations are correct, PlanetLab and Simulation results were tested in addition to much larger networks, as shown in Figure 3-6. Timing is based upon the typical connection steps when connecting to the public overlay, querying the DHT, and then connecting to the private overlay using this process as the basis for our evaluation.

The results, Figures 3-5, 3-6 are well correlated with near identical slopes. In all cases the time to become connected with the private overlay remains reasonable and scales logarithmically as network size grows. Connection times differ amongst the sets, in the case of the Simulator all the state machines are at the maximum wait delay due to lack of churn in the system, whereas PlanetLab has limited overhead due to this delay, and the modeler does not worry about state machine state, churn, or bad connection attempts. An important result is that PtP security does not significantly add to time to

joining the overlays, most likely due to the majority of the time being occupied by overlay routing.

3.7.2 Instantaneous Pool Creation

This experiment determines the amount of time required to bootstrap a private overlay including their matching public overlay nodes using an existing network. The experiment starts with a public network size of 200 public nodes with various amounts of additional nodes that also have a private overlay pair. Because PlanetLab is difficult to control in terms of attempting to start 200 public nodes simultaneously and ensuring that they do not restart mid-experiment, this experiment was run using the simulator.

Figure 3-7 presents the results with and without security for various sized networks. The results present a slightly different picture than the previous experiment. In this case, there is a slightly logarithmic growth to the time it takes to complete an overlay. As in the previous test, the use of security has a small relative impact on the overall time to form the ring.

3.7.3 Measuring Bandwidth

This experiment reuses the overlay bootstrapped in the previous experiment and measures bandwidth for 60 minutes, the 60 minutes after the overlay is well-formed. Reusing the simulation results changes has no effect on the results of this experiment and cuts down on the most expensive part of the procedure, the bootstrap phase. The results are shown in Figure 4-15.

As shown in Figure 4-15, when comparing the querying of the DHT using static and dynamic timers, the static timer's bandwidth is dominated by DHT queries. Since the system is at steady state, i.e., no new nodes in the system, only a single DHT query is made using dynamic timers. In both cases, the time to form a complete ring as performed in Section 3.7.2 is the same. The dynamic timer causes bandwidth to grow slower than a logarithmic pace. Given that the bandwidth used grows slowly, it

appears that overlays in general use negligible amounts of bandwidth and that even using security does not increase it significantly.

In regards to selecting a proper timeout, it can logically be surmised that if an existing public and private overlay were going through heavy churn, there will always be a base of nodes connected to each other. If because the DHT is currently fragmented, a new node forms a partitioned private overlay, the node should eventually and quickly find out about the original overlay and reform the split overlays due to the continuous queries. The advantage of the dynamic timeout is that it places the weight for fixing ring partitions on the nodes that created them rather than the older more stable nodes.

3.7.4 Evaluating Revocation Implementations

Figures 3-9 and 3-11 present the time required and network traffic to perform a revocation using the simulator and modeler, respectively. The values were determined by setting the estimated average size of a revocation to 300 bytes , which includes information such as the user's name, the group, time of revocation, and a signature from the CA's private key. To evaluate the cost in simulations, the bandwidth was mesaured for 30 seconds that included the revocation and 30 seconds where there was no activity. Ths time sample was chosen because it represented the smallest amount of time that would contain a representative steady state bandwidth but also make the cost of revocation obvious. The modeler only contains total bytes required for the operation because no connection based steady state behavior is modeled.

The results seem to indicate that in terms of time, network size and bandwidth scale well together. In contrast, the network traffic scales significantly better in DHT experiments, though the approach can be inefficient for environments consisting of malicious and colluding peers. In a DHT revocation, revoked peers can attempt to connect with new peers who do not know about the revocation, causing each of them to query the DHT to discover the revocation. If this becomes the case, the DHT method will quickly become inefficient. On the other hand, the broadcast cannot ensure that all

nodes receive the message, due to overlay network stability issues, peers may not be included in the broadcast. As such the best approach may be to store a revocation in the DHT but notify all peers of a revocation via a broadcast. Broadcast is efficient with bandwidth, because the broadcast forms a tree, which spans exactly N-1 connections. The network traffic required to do a broadcast on this tree is the minimum amount of communication necessary to reach all nodes in the broadcast range.

3.8 Related Work

BitTorrent [6], a P2P data sharing service, supports stream encryption between peers sharing files. The purpose of BitTorrent security is not to keep messages private but to obfuscate packets to prevent traffic shaping due packet sniffing. Thus BitTorrent security uses a weak stream cipher, RC4, and lacks peer authentication as symmetric keys are exchanged through an unauthenticated Diffie-Hellman process.

Hamachi [59] provides central group management and a security infrastructure through a Web interface. Their security system has gone through two revisions as documented in [61]. Initially peers learn of each other through Hamachi's central system, which leads to the creation of secure links. In their original approach, they use a system similar to a Key Distribution Center (KDC), which requires that all security sessions initiate through Hamachi's central servers. In the latest version, this model has been retained but with the addition of an external PKI, which avoids the man-in-the-middle attack but with has the additional cost of maintaining both an external CA and certificate revocation list (CRL). Hamachi also supports STUN, or NAT hole punching, and TURN style NAT traversal, though TURN requires the use of Hamachi's own relay servers. Because Hamachi is closed, it disables users from hosting their own infrastructures including session management and relay servers.

Skype [56], like P2PSIP, allows for decentralized audio and video communication. Unlike P2PSIP, Skype is well-established and has millions of users and is also closed. While Skype does not provide documentation detailing the security of its system,

researchers [31, 40] have discovered that Skype supports both EtE and PtP security. Though similar to Hamachi, Skype uses a KDC and does not let users setup their own systems.

The RobotCA [5] provides an automated approach for decentralized PKI. A RobotCAs receives request via e-mail, verifies that the sender's e-mail address and embedded PGP key match, signs the request, and mails it back to the sender. RobotCAs are only as secure as the underlying e-mail infrastructure and provide no guarantees about the person beyond their ownership of an e-mail address. A RobotCA does not provide features to limit the signing of certificates nor does it provide user-friendly or intuitive mechanisms for certificate revocation.

Distributed data store applications like [21, 24] require that all machines have symmetric connectivity additionally like [78], suggesting the use of a third party application to ensure trust amongst all overlay participants. This is an example use case that is explicitly targeted by our system on the presumption that there are not sufficiently easy to use decentralized VPN software applications [89, 91] and even if there were it is undesirable to have additional setup requirements.

There are many approaches that propose using public overlays to create sub-overlays [20, 53, 70, 72]. The approach described in [20] proposes the use of a universal overlay as a discovery plane for services, their emphasis on applications, that users in the public overlay support the minimum overlay features, whereas the other overlays are application specific. Similarly, Randpeer [70] uses a common overlay along with a subnetting service to create individual networks for applications and services, though the project has seen little activity and lacks implementation details. Unlike the previous two, [72] limits the sub-overlay for the purpose of establishing multicast groups, though their approach lacks discussion on how nodes discover and form a new overlay as such their approach is limited to simulations. Simiarly [53] is limited to simulations, the focus is on peers being able to form their own overlays for performance purposes and

does not discuss implementing in an actual overlay. My approach allows for an entire overlay to exist amongst peers behind NATs, uniquely distinguising my work from these approaches, in addition, I have implemented my approach and tested in real systems.

3.9 Figures and Tables

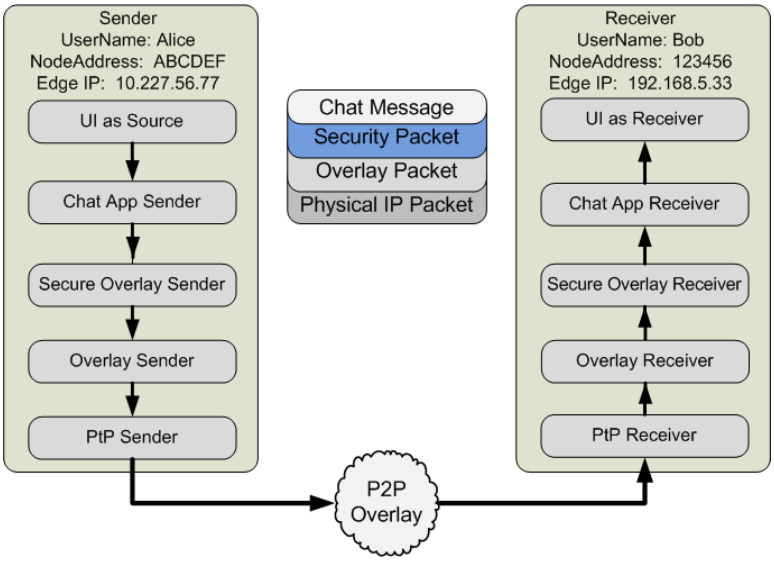


Figure 3-1. An example of the abstraction of senders and receivers using a EtE secured chat application. Each receiver and sender use the same abstracted model and thus the chat application requires only high-level changes, such as verifying the certificate used is Alice's and Bob's, to support security.

	Latency (ms)	Bandwidth (Mbit/s)	
DTLS CBC	0	0	
Our CBC	0	0	

Table 3-1. CBC Issue – In Progress.

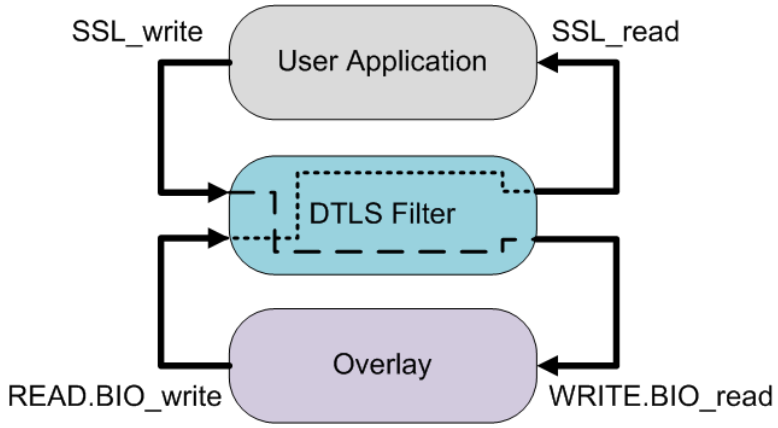


Figure 3-2. The DTLS Filter. To send a secure message, execute SSL_write and retrieve the encrypted packet at the WRITE BIO via a BIO_read. To verify and decrypt a packet, execute BIO_write on the READ BIO and retrieve the packet via SSL_read. When SSL_write or SSL_read return the error WANT_READ. This means that either it is waiting for a control message or one is available at the WRITE BIO. If a message is retrieved from the WRITE BIO, it is a control message. Because DTLS does not provide reliability when using the memory BIO, control messages should be sent using a reliable medium, such as a light-weight request/reply system.

Figure 3-3. Steps in joining a private virtual overlay.

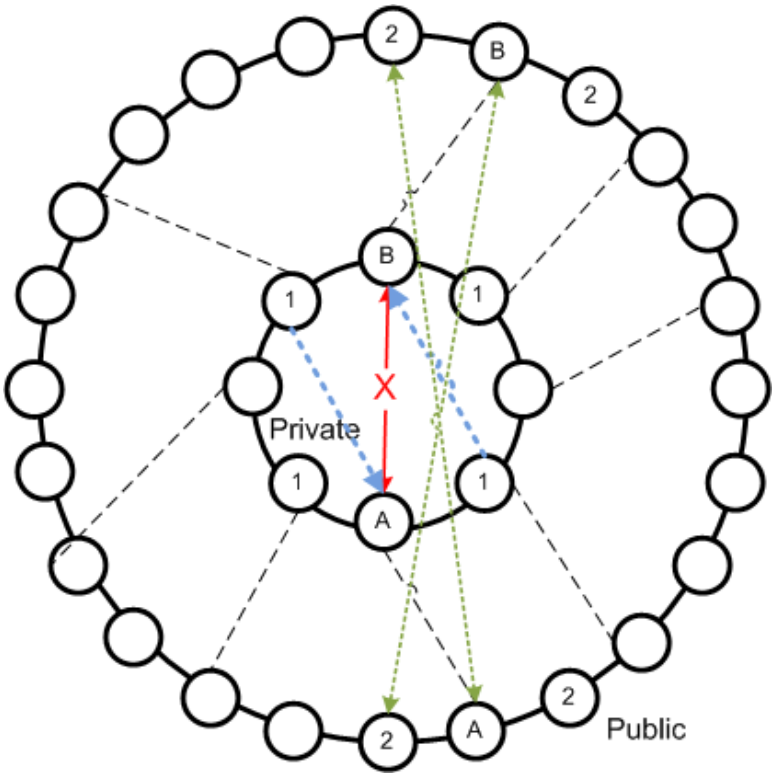


Figure 3-4. Relays in subring environments. Creating relays across the node address space, when direct connectivity is not possible. Two members, A and B, desire a direct connection but are unable to directly connect, perhaps due to NATs or firewalls. They exchange private, 1, and public, 2, neighbor information through the private overlay and connect to one of each other's neighbors, creating an overlap. The overlap then becomes a PtP relay path (represented by directed, dashed lines), improving performance over routing across the entire overlay.

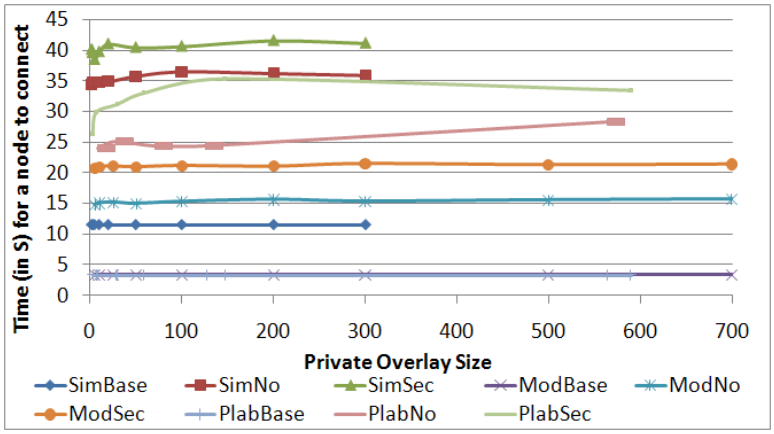


Figure 3-5. The time it takes for a single node joining a public overlay and then a private overlay. Since the public overlay size is the same in all tests, we averaged all results together for the individual evaluations. The format for the legend is defined using the following convention: EnvironmentOverlay, where the environment is PlanetLab, Simulator, or (Network) Modeler and overlay is Base for public overlay, No for no security private overlay, and Sec for security enabled private overlay. ModBase is network modeler Public overlay connection time. SimSec is simulator security enabled private overlay.

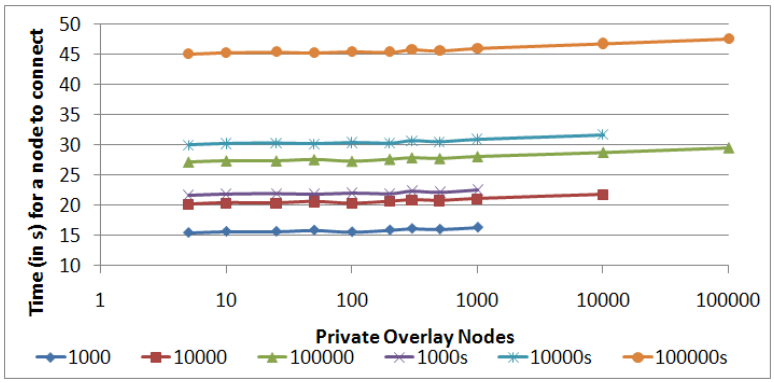


Figure 3-6. The time it takes for a single node joining a public overlay and then a private overlay. The X axis represents the number of peers in the private overlay, whereas the lines themselves represent the number of peers in the public overlay. The legend for the line consists of “number[s]”, where the number represents the total numbers of peers in the public overlay and the optional “s” specifies whether the private overlay is modeling security.

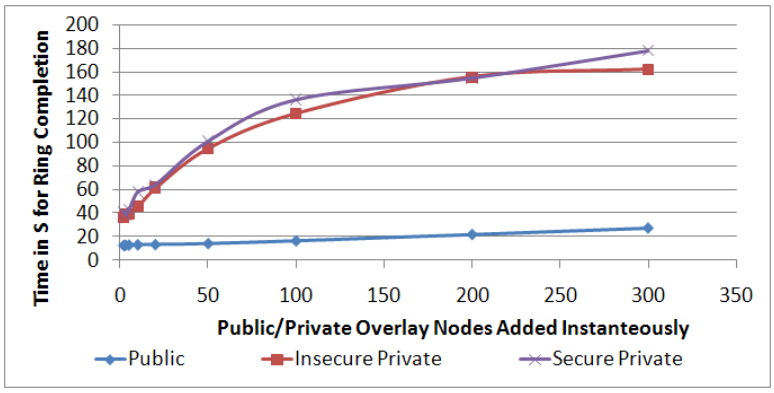


Figure 3-7. The time to form private overlay using a public overlay with 200 nodes after simultaneously turning on various counts of private overlay nodes.

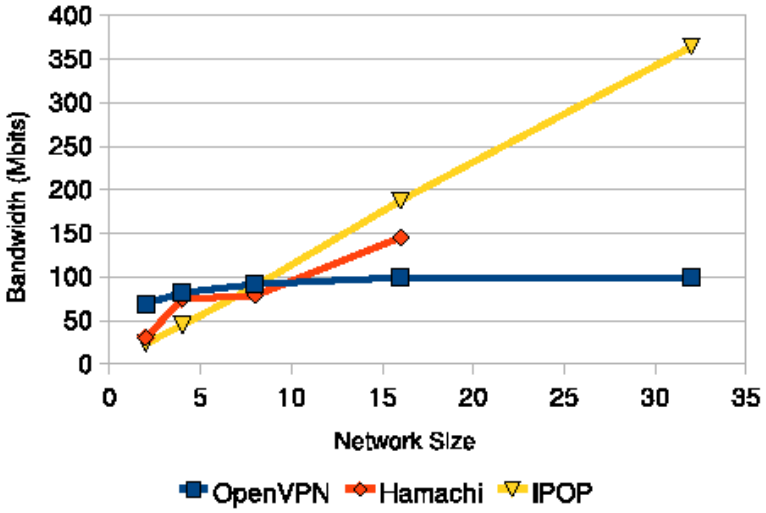


Figure 3-8. Bandwidth used in a systems with and without security during steady state operations consisting of 200 public nodes and various sized paired public / private nodes. Those lines labeled “static” have DHT lists queried every 5 minutes whereas in “dynamic” queries are made using an exponential back-off policy starting at 30 seconds up to a maximum of 60 minutes. Bandwidth is in bytes / second, a negligible amount of bandwidth for DSL and Cable Internet.

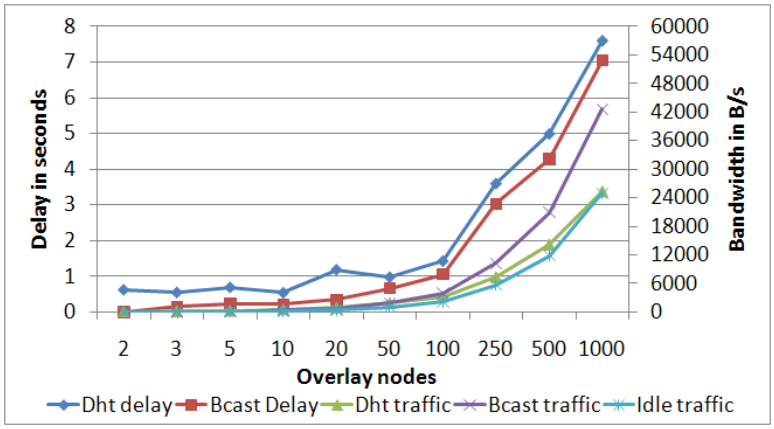


Figure 3-9. The time delay and bandwidth used during the time between revoking a node and notifying nodes of the revocation using simulations. (Broadcast has been abreviated to “Bcast”).

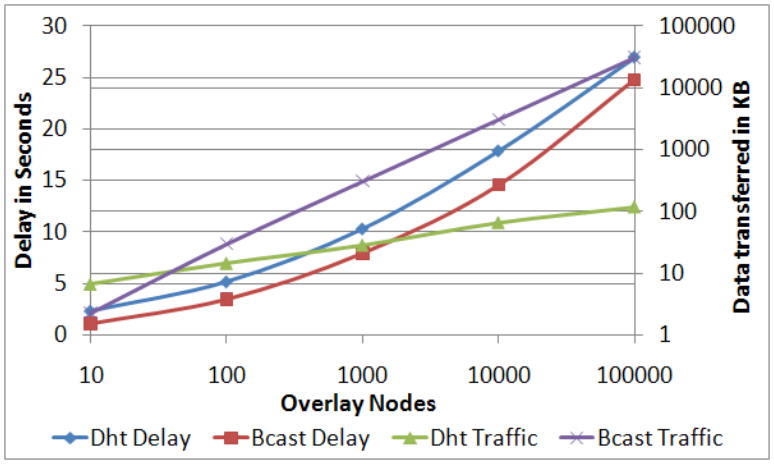


Figure 3-10. The time delay and bytes transferred during the time between revoking a node and notifying nodes of the revocation using the modeler. (Broadcast has been abreviated to “Bcast”).

Figure 3-11. Time required and bytes transferred during a modeled DHT and broadcast revocation.

CHAPTER 4
AUTONOMIC VPNS

In distributed computing, there are many applications for VPNs, two such tasks are the connecting large sets of remote resources and accessing a central server or a personal resource. Similar use cases can be extrapolated onto other collaborative environments such as multiplayer games, merging home networks over a VPN, or accessing a work computer remotely. Each application has different requirements and in review of related research [25, 35, 38, 46–48, 58, 59, 67, 74, 81, 85–87, 92] not a single approach efficiently supports these dynamic environments. Certainly ISP large scale VPNs such as MPLS [4] do not as well. An overview of these and the one described in this proposal are presented in Table 4-1

The organization of a VPN has a direct effect on the amount of user effort required to connect multiple sites. In this regard there are two components of a VPN, the local organization and the remote or network organization. The setup of the virtual network in order to have be a destination and recognized source for remote packets consitute the local organization. Whereas the routing of the packets amongst peers is handled by the network organization. Prior research works primarily focused on the latter issue, while ignoring the former. This meant that users were left setup their own address allocations either through manually configuring each environment or dealing with the head aches of caused by DHCP servers in cross domain network construction as well as their own security distribution systems. In addition, organizing a network can be an even more complicated task than locally configuring the network. This chapter presents a novel approach to VPNs that achieves both local and network self-configuration.

4.1 Network Configuration

The key to communicating in a VPN is creating links to the VPN and finding the peer in the VPN. The different architectures for VPN link creation are based on

distributed computing communication methods and are described in Table 4-2. The approaches are described in more detail below.

4.1.1 Centralized VPN Systems

OpenVPN is an open and well-documented platform for deploying centralized VPNs. We use it as the basis for understanding centralized VPNs as it represents features common to most centralized VPNs. In centralized VPN systems, clients forward all VPN related packets to the server. Clients responsibilities are limited to configuring the VN device and authenticating with the VPN server; whereas the servers are responsible for authentication and routing between clients and providing access to the servers' local resources and the Internet (full tunnel).

While central VPNs do support multiple servers, the client must know of all existing servers randomly selects a server, implementing a simple load balance. Once connected, servers hand to the client an IP address in the VPN address space. Depending on configuration this will allow a client to communicate with other clients, resources on the same network as the server, or Internet hosts via the VPN. Additionally, servers must be configured to connect with all other servers otherwise clients behind remote servers will not be able to communicate with each other.

All inter-client communication flows through the central server. By default, a client encrypts a packet and sends it to the server. Upon receiving the packet, the server decrypts it, determines where to relay it, encrypts it, and then sends the packet to its destination. This model allows a server to eavesdrop on communication. While a second layer of encryption is possible through a shared secret, it requires out-of-band communication and increases the computing overhead on communication.

4.1.2 Centralized P2P VPN Systems

Hamachi [59] is the first well known centralized VPN that used the ambiguous moniker "P2P VPN". In reality, these systems would be best classified as centralized VPN servers with P2P clients. Other similar VPNs include Wippien [67], Gbridge [58],

and PVC [74]. Specifically, P2P in these systems is limited to direct connectivity between clients orchestrated through a central server. In the case where direct connectivity is unavailable due to NATs or firewalls, the central server can act as a relay and if not peers will be unable to communicate. Each approach uses their own security protocols that involve using a server to verify the authenticity and setup secure connections between clients. Furthermore, most of these projects are closed preventing users from hosting their own authentication servers and relays and verifying the code for security purposes forcing users to trust the third-party server to not eavesdrop or perform other man-in-the-middle attacks.

4.1.3 Decentralized VPN Systems

Some examples of systems that assist in distributing load in VPN systems are tinc [81], CloudVPN [30], ViNe [87], VNET [85], and Violin [46]. These systems are not autonomic and require explicit specification of links between resources. This means that, like OpenVPN, these systems can suffer VPN outages when nodes go offline, thus administrators must maintain the VPN connection table. Unlike OpenVPN, these approaches typically do not require all-to-all direct connectivity for all-to-all communication. Users can either setup out-of-band NAT traversal or route through relays. Users must manually create links with those whom they desire maximum network performance.

4.1.4 Unstructured P2P VPN Systems

Unlike centralized and decentralized systems, P2P environments are self-configuring requiring the only task for the user is to connect to the P2P overlay. The most simplest form of overlays are unstructured, where peers form random connections with each other and use broadcast and stochastic techniques to find information and other peers, though due to its unstructured nature, the system cannot guarantee distance and routability between peers. Two examples of unstructured P2P VPNs are N2N [25] and

P2PVPN[1] [38]. P2PVPN is somewhat of a hybrid using a centralized BitTorrent tracker to assist in peers finding each other, they eventually will also be able to search for each other using the overlay. In N2N, peers first connect to super nodes and then to find another peer they broadcast discovery messages to the entire overlay. In the case that peers cannot form direct connection, peers can route to each other over the N2N overlay. While unstructured P2P systems have some scalability concerns, they provide a server-less approach. In the realm of VPNs, all client VPNs are also servers performing authentication though neither approach deals with decentralized address allocation.

4.1.5 Structured P2P VPN Systems

To address the scalability concerns in unstructured systems, this work uses structured P2P overlays. As described in Chapter 2, structured P2P overlays provide distributed look up services with guaranteed search time with a lower bound of $O(\log N)$, in contrast to unstructured systems, which rely on global knowledge/broadcasts, or stochastic techniques such as random walks. In general, structured systems are able to make these guarantees by self-organizing a structured topology, such as a 2D ring or a hypercube, deterministically by randomly generated node identifiers.

The primary feature used by structured overlays is a distributed data store known as a distribute hash table (DHT), which stores key, value pairs. In the overlay, the key is an overlay address, where the value is stored. The peer closest to the key's overlay address is responsible for maintaining the value. Cryptographic hashes like SHA and MD5 can be used to obtain the key's overlay address from a string or some other byte array.

[1] Due to the similarities between the name P2PVPN and focus of this proposal, we use "P2PVPN" to refer only to [38] and "P2P VPN" to refer explicitly to the use of P2P in VPNs.

In [37, 83], a method for address allocation is described by using the DHT. Each VPN has a unique name or namespace, when a peer requests an IP address, a mapping of $hash(namespace, IP)$ to the peers overlay address is atomically written to the DHT. A success implies that the writer was the first writer to that value and other peers reading that value will be able to indentify that peer as owner of that IP address in that namespace. Likewise when a peer wants to route a packet to a remote VPN peer, they query the DHT using the mapping, which returns the overlay address. The IP packet is then sent to the overlay destination.

Unicast messages are sent between two end points on the overlay using normal overlay routing mechanisms. Direct overlay links can be used to improve performance between end points. [35] describes a method by which peers can form autonomic direct connections with each other using an unstructured overlay. As IP traffic increases over a period of time, a direct connection to bypass the overlay is initiated by the receiver of the packets. Alternatively, a VPN may wish to form all-to-all connections with VPN peers as described in [32].

To support broadcast and multicast in an overlay, all members of a subnet associate through the DHT by placing their overlay address at a specific key, i.e., $namespace : broadcast$. Then when such a packet is received, it is sent to all addresses associated with that key. It is up to the VN at each site to filter the packet. This is sufficient to support deployments where multicast or broadcast is not relied upon extensively.

4.2 Local Configuration

From a superficial point of view there are two approaches to local VPN configuration a single VN endpoint per a host (Interface) and a VN router endpoint for many hosts on the same LAN (Router). The components differing between the two approaches are:

- **Software location** - Interfaces execute the software on each VPN connected resource, whereas any machine connected to the same LAN as a Router will be able to access the VPN. The Router requires a dedicated resource.

- **Network configuration** - Since the Interface software runs on each machine, it is able to directly configure networking parameters, whereas a Router must use external methods to configure the resources.
- **Communication on a LAN** - When two peers on a LAN using a VPN Interface to communicate, all traffic must pass through the VPN adding unnecessary overhead, though in a Router the two peers have a merged physical and virtual network between them and the traffic is able to bypass the VPN.
- **Fault tolerance** - The Router only has a single instance running, when it goes offline, all resources will lose their VPN access, whereas each individual resource has their own Interface and is responsible for their own VPN connectivity.
- **Communication over the WAN** - Performing encryption can be expensive and may limit the bandwidth available due to CPU constraints. A Router may struggle to use all the available bandwidth, whereas enough Interfaces will eventually be able to use all the bandwidth. Although each additional VPN Interface also has idle traffic, potentially reducing usable bandwidth.

This proposal identifies methods by which a single software stack can be implemented to support self-configuration and resource migration in a way that is platform independent. This method lends itself to a new architecture known as Hybrid, allowing an instance to be run on each VPN resource but enabling direct communication amongst peers on a LAN as described in [91]. The architectures are shown communicating via an overlay in Figure 4-1 and compared in Table 4-3. The two aspects that need configuration in the local configuration beyond the VPN architecture are address allocation, obtaining and setting an IP address on a resource, and address resolution, determining where to route a VPN packet. The keys to creating this environment involve the use of standard network protocols implemented uniformly across operating systems, including DHCP (dynamic host configuration protocol) and ARP (address resolution protocol). Many applications make use of names instead of IP addresses to resolve peers, as such a naming system, like DNS (domain name service) is almost as important as address resolution and allocation. A state machine representation of this architecture is shown in Figure 4-2.

4.2.1 Local VPN Architecture

As described in the introduction, the TAP device is the glue by which the local resources communicate with the VPN. Each approach relies on the TAP device though in different configurations. In the Interface (Figure 4-3), the TAP device is used directly by the user as any other network device. In short, packets are written to the TAP device by the O/S sockets and read by the VPN software to send to the remote location, packets received by the VPN are written to the TAP device and delivered to sockets by the O/S. The Router (Figure 4-4) bridges the TAP device to a LAN, thus packets can be routed to it and sent through the VPN. TAP device virtualizes a bridge to other physical networks.

Finally, the Hybrid (Figure 4-5) like the Router connects to the LAN but only allows configuration from the local host. In Linux this is possible through the use of a VETH pseudo device that provides a virtual Ethernet pair, so that one end can be bridged with the TAP device and LAN while the other provides another interface that can be configured on the LAN, which will be used by the VPN. The reason for this lies in the nature of the state of the interfaces connected to the bridge, which go into promiscuous mode, so that all packets sent to them are forwarded on as if they are on a wire as if there were only a single network interface. In non-promiscuous mode, the network card will drop packets that are not destined for that network card. So in that case, it is not possible to assign more than one IP address to a bridge, because it and all devices connected to it are viewed as one big network interface. Connecting the VETH device allows an additional uniquely identifiable Ethernet addresses and thus additional IP addresses. In contrast, aliasing a Ethernet card only provide additional IP addresses and services that rely on layer 2 networking. In this case, some services may not work, for example, DHCP does not work on aliased network cards.

4.2.2 Address Resolution

IP is a layer 3 protocol. Layer 2 devices such as switches, bridges, and hubs are not aware of IP addresses. When a system wants to send a layer 3 packet over a layer 2 network, it first uses ARP to find the layer 2 address owning the layer 3 address. This process, as shown in Figure 4-6, begins by the sending of a layer 2 broadcast message which contains an ARP request, asking all members in the LAN that the node owning the target IP address respond to the sender of the request. If a node owns the target IP address, it responds with an ARP reply, making themselves the sender and the original sender is the message recipient. The Ethernet header consists of the source address being the sender and the target being the destination. By listening to these requests, layer 2 devices such as a switch can autonomously learn the location of nodes holding Ethernet addresses are and can forward packets through appropriate ports as opposed to broadcasting or dropping them.

In a typical IP subnet, all machines talk directly with each other through switches. As such, they must learn each other's Ethernet address. The VN model used in this proposal focuses on a large, flat subnet spanning across all nodes connected to the VPN. To accomplish this, the VN provides the ability to virtualize a bridge, similar to proxy ARPs [68] used to implement a transparent subnet gateway [17]. In this scenario, the VN would need to respond to the ARP packets with a fake layer 2 address. Layer 2 devices in the system would then route all packets destined for that layer 2 address to the VN.

As shown in the state machine (Figure4-2), ARPs are only responded to if (a) they are inquiring about a VN IP address, (b) the VN address is not locally allocated, and (c) there is a P2P:IP mapping. If all those are true, then an ARP response is sent back to the sender. ARPs are occasionally sent out during the course of communication and thus if a machine migrates to a VN router, the VN router will no longer respond with ARPs. An ARP response sent by the VN requires a source Ethernet address, bridges

and switches will see the response and will forward all traffic towards the TAP device for that Ethernet address. A VN device can use the same Ethernet address for remote entities.

Prior to the introduction of the VN hybrid, the VNs used the Ethernet address FE:FD:00:00:00:00 to refer to remote entities. If each VN hybrid used this address, there would be layer 2 collision causing a single hybrid to have all traffic sent to it. In hybrid mode, each VN must generate a unique "remote" Ethernet address at run time. Our experience and research has led us to the following solution: (1) use FE:FD for the first two bytes as they tend to be unallocated and (2) assign random values to the 4 remaining bytes. Applying the birthday problem in this context, the expected probability of address collisions is small for typical LAN environments (less than 50% if the average number of VN hybrid nodes on the same L2 network is 65,000).

The key difference from the Hybrid and Router is that the Hybrid routes for only a single node, say "A", and thus msut ignore messages that do not originate from "A". The Hybrid model does not necessarily know about the existence of all machines in a LAN, because it does not own them. So when an ARP request of some remote machine, say "B", is sent by "A", the Hybrid must send out a matching request with the result being sent back to the pseudo-entity of the transparent subnet gateway so that the VPN can determine if "B" exists locally. If no message is returned after a set amount of time (the reference implementation used 2 seconds), then assuming that there is a peer in the overlay with the IP address, the original ARP will be responded to with the pseudo-entity being the target.

4.2.3 Address Allocation

IP addresses are traditionally allocated in one of three ways: 1) statically, 2) dynamically through DHCP, or 3) through pseudo-random link-local addressing. This model foucses on static and dynamic addressing.

The network components configurable by DHCP as defined by [11, 29] that are interesting to a VPN are addresses, routing, and other networking related features. While many different client and servers exist, they all tend to support the basic features of allowing the server to specify to a client and IP address, a gateway address, and domain name servers. As shown in Figure 4-7, the steps in DHCP are:

1. Client sends Discover packet requesting address.
2. Server receives the packet, allocates an address, and sends an Offer of the address and other network configuration.
3. Client receives and acknowledges the Offer by sending a Request message to accept the Offer.
4. Server receives Request message and returns an Ack message containing the same details as the Offer.

During the DHCP phase, the VPN communicates with a DHCP server for the VPN, which will allocate an address for the requester. Similarly, a VN model can review packets coming into the VPN, review the sender IP address, and request and notify the server of this allocation. Treating static addresses like DHCP enables easier configuration of the VPN, though it is difficult to handle address conflicts. In this model, this is done by the server ignoring the duplicate requests, and it is up to the user to configure for a new address. Thus DHCP provides a more reliable method in these systems.

To support scalably handle address allocation in decentralized systems, the DHCP server is a virtual entity, parsing DHCP packets and interacting with an overlay based DHT. This approach does not need to be limited to structured overlay based VPNs but can be introduced as an added value component.

An important aspect of DHCP is that after a machine has received an IP address from the DHCP server, it always checks to ensure that the address has not been allocated, as such the VPN should never respond to address resolutions for local IP addressses.

If an overlay allocates an address to the VN, then the VN owns it. The other address that the VN owns is the null address, 0.0.0.0, which is sent during DHCP to indicate that the machine has no address prior to the request.

4.2.4 Domain Name Servers and Services

Name services allow machines to be addressed with names that are more meaningful to users than numeric addresses. Certain applications and services require domain name checking, such as Condor. To support DNS, this requires that the OS be programmed with the VN's DNS servers IP, which we take generically to be the lowest available IP address in a subnet. In static configuration, this process requires the user to manually add this address, though through DHCP this is set automatically.

In the state representation of the VN (Figure 4-2), the VN checks the IP packet to ensure that the destination IP and port match that of the virtual DNS server and the well-known DNS port, 53. In the event of a match, the packet is passed to the VN's handler for domain names. From our experience, there are two common uses for names, 1) because applications require it, and 2) to assist users in finding resources. For 1), we have implemented a system that takes in an IP address and maps it directly to a name, such as, 10.250.5.5 maps to C250005005. For 2), we take advantage of the DHT and perform a Put in the key namespace:hostname with the value being the mapped IP address.

4.3 Supporting Migration

There has been a rapid increase in the deployment of Virtual Machines (VMs) for use in resource consolidation in the server industry as well as the domain of cloud computing. Providers of cloud computing services have adopted virtual machines as the unit of granularity for providing services and service level agreement to the users. Users are billed according to the number of VMs and their uptime. Major cloud-computing providers including Amazon EC2 and Go-Grid have adopted Xen as the virtualization platform for their services and sell compute resources in the form of virtual machines.

Apart from advantages like performance isolation, security, and portability, one of the significant advantages of using VMs is the capability to migrate the VM with its entire software stack from one physical host to another. This migration may be performed in a stop-restart manner, where the VM is paused, migrated to another host and restarted, or in a live mode, which attempts to minimize down time to reduce interruption of services running on the VM.

VMs including Xen [51], VMware ESX [64] and KVM [69] support migration with two critical requirements: (1) file systems (disk images) must be on a shared storage system (i.e. network file systems or storage area networks) and (2) to maintain network connectivity, the migration must occur within an IP subnet. In order to retain network connectivity after migration, the VMM must notify the LAN of the VM's new location. The new VMM host generates an unsolicited ARP reply which broadcasts to the entire network the VM's new location.

The VN Interface and Hybrid models support migration of the virtual address using techniques previously described in [35]. This is a product of the decentralized, isolated overlay approach where each overlay end point has a one-to-one mapping to VN end point, e.g., P2P to IP. When a VN Interface or Hybrid model migrates, the overlay software must reconnect to the overlay, at which point, packets will begin to be routed to the VN endpoint again, completing migration.

Unlike Interface and Hybrid models, the VN Router does not support a one-to-one mapping. In fact, a VN router tends to have one P2P address for many IP addresses. When a machine with a VN IP wants to migrate, it cannot also take its P2P address with it otherwise it would end connectivity for the rest of the members of the VN router shared overlay end point. A solution to this problems requires the ability to delete IP-to-P2P mappings in the DHT, detect new addresses on the network, and inform senders that an IP is no longer located at that overlay end point. With these capabilities, transparent migration can be achieved for the VN router model as follows.

The VMM initiates a migration on a source node. Until the migration completes, the VN router at the source continues to route virtual IP packets for the VM. Upon completion of migration, the VN router at the target learns about the presence of the migrated VM by either receipt of an unsolicited ARP or by proactively issuing periodic broadcast ICMP messages on its LAN. The VN router attempts to store (Put) the IP:P2P address mapping in the DHT, and queries for the existence of other IP:P2P mapping(s). If no previous mappings are found, the VN router assumes responsibility for the IP address. Otherwise, the VN router sends a migration request to each P2P address returned by the DHT. The VN router receiving a migration request confirms the existence of the IP address in its routing table and that if there is that there is no response to ARP requests sent to the IP address. If these conditions hold, it deletes its IP:P2P mapping from the DHT and returns true to the migration request; otherwise, it returns false. If the migration request returns true, the VN router at the target LAN starts routing for the virtual IP address; if it returns, false, the VN router does not route for the virtual IP address until the previous IP:P2P mapping expires from the DHT.

In addition to VN routers synchronizing ownership of the migrated virtual IP address, any host that is connected to that machine must be informed of the new P2P host. Over time, this will happen naturally as ARP cache entries expire and the IP:P2P mapping is looked up from the DHT. Additionally, the VN router at the source may keep forwarding rules for the migrated IP address for a certain period of time, akin to mobile IP but not on a permanent basis. A more direct approach, as implemented in the prototype, involves the VN router notifying the connected host of a change in ownership, resulting in the host querying the DHT for the updated P2P end point. An evaluation of tradeoffs in the migration design, while interesting, is outside the scope of this paper.

A static address allocation is similar to a migration without there being an IP:P2P value in the DHT, though without querying the DHT, the situation is unclear. Systems

that use DHCP only must have some method for detecting new addresses, because there is no guarantee that a DHCP will occur immediately following migration, in fact, depending on the lease time that is highly unlikely. Using an insecure DHT that supports deletes is sketchy as it would be relatively easy for machines to perform man in the middle attacks by deleting keys which they do not own. Even the use of passwords mentioned in DHT literatures is not sufficient as it is not immune to collusion, or Sybil, attacks.

VN router migration was analyzed through the use of two Xen-based VMware VMs co-located on the same quad-core Xeon 5335 2 GHz machine each with 1 GB memory allocated using a minimally configured OS with a SSH server. The evaluation attempts to understand overlay overheads of the approach. The experiment, as shown in Figure 4-8, involved migrating a Xen guest VM between two Xen host VMMs running in VMware. Although they are hosted in the same infrastructure, the two domains are connected to two separate VLANs, and thus isolated. The reosurce information is stored in a DHT running on top of PlanetLab. Thus the migration overheads in the experiment capture the cost of wide-area messaging in a realistic environment. During the course of the experiment, over 50 different IP addresses were migrated 10 times each in an attempt to gain some insights in the cost of using the DHT with support for deletes and VN router messages as a means to implement migration. The result, presented in Figure 4-9 gathered from the experiment was how long the VN IP was offline, measured by means of ICMP ping packets. On average, the overhead of VN migration was 20 seconds. This overhead is in addition to the time taken to migrate a VM, since the VN routers begin to communicate only after migration finishes.

4.4 Enhancing the Structured P2P VN with Private Virtual Overlays

The use of group enabled private virtual overlays enable two qualities for VPN: user-friendly security and more efficient methods for broadcast and multicast IP communication.

4.4.1 Securing the VPN Through Groups

The premise for secure a structured overlay VPN extends from the work on group enabled private virtual overlays. Each VPN will use a unique private overlay secured by a group-enabled PKI. For VPN purposes, both the overlay control messages are encrypted as well as IP traffic, protecting the overlay from malicious third-parties but all the IP traffic between two members from other members.

The group overlay model requires a few modifications to be applied to a group VPN. During the creation of the group, the administrator configures the VPNs address range, namespace, enabling security, and if they would like to use an existing public overlay network or provide their own set of overlay nodes. When a user has been accepted into the group, they are able to download VPN configuration data, which is used to self-configure the VPN. The configuration is self-contained and requires that the user provide it to the VPN, by either placing it in a specific directory, a GUI, or a command-line utility whose only input parameter is the path to a configuration file.
In the prototype, the only the file system and command-line approaches have been implemented. The configuration data contains the IP address space, VPN namespace, group website's address, and a shared secret. The shared secret uniquely identifies the user, so that the website can determine how to handle certificate requests. When making a certificate request, the user sends over HTTPS a public key and their shared secret, the website creates and signs a certificate request based upon the public key and the user's relevant information ensuring that users cannot trick the website into signing malicious data. Upon receiving the signed certificate, peers are able to join the private overlay and VPN enabling secure communication amongst the VPN peers.

4.4.2 Broadcasting IP Broadcast and Multicast Packets Via the Overlay

The use of a private virtual overlay enables a new method for sending multicast and broadcast packets. Instead of using unicast overlay messages to share IP broadcast and unicast messages, the same method used to perform broadcast revocation,

described in Appendix 7, can be used to efficiently distribute these messages. Though in VPN situations, many peers may already have connections to most if not all of their VPN peers, thus the broadcast algorithm must be modified to route to only connections created for structured overlay purposes and not explicitly only for VPN purposes. Otherwise in many cases, this algorithm will degenerate into one similar to the previous approach. As shown by Figure 4-10, the approach scales significantly better, though the approach still lacks intelligent path creation for bandwidth heavy applications.

4.5 Full Tunnel VPN Operations

The configuration detailed so far describes a split tunnel: a VPN connection that handles *internal VPN traffic only, not Internet traffic*. Prior to this work, only centralized VPNs currently support full tunnel: providing the features of a split tunnel in addition to securely forwarding *all their Internet traffic* through a VPN gateway. A full tunnel provides network-layer privacy when a user is in a remote, insecure location such as an open wireless network at a coffee shop by securely relaying all Internet traffic through a trusted third party, the VPN gateway. Both models are illustrated in Figure 4-11.

Central VPN clients use full tunneling through a routing rule swap, setting the default gateway to be an endpoint in the VPN subnet and traffic for the VPN server is routed explicitly to the LAN gateway. This rule swap causes all Internet packets to be routed to the VN device and the VPN software can then send them to the remote VPN gateway. At the VPN gateway, the packet is decrypted and delivered to the Internet. A P2P system encounters two challenges in supporting full tunnels: 1) P2P traffic must not be routed to the VPN gateway and 2) there may be more than one VPN gateway. We address these issues and provide a solution to this problem in Section 4.5.

The challenges we face in our VPN are providing decentralized discovery of a VPN gateway and supporting full tunnel mode in a P2P environment such that all P2P traffic is sent to the intended receiver directly instead of through the gateway. The remainder of this section covers our gateway and client solutions to address these challenges.

4.5.1 The Gateway

A gateway can be configured through NAT software, like masquerading in IPtables or Internet Connection Sharing with Windows. This automatically handles the forwarding of packets received on the NAT interface to another interface bringing the packet closer to its destination. Similarly, incoming packets on the outgoing interface must be parsed in order to determine the destination NAT client.

Following from the original design of the VPN state machine in Figure 4-2, if a VPN is a gateway, the VPN state machine no longer rejects packets, when the destination is not in the VPN subnet, though when the VPN gateway mode is disabled these packets are still rejected. When enabled, all Internet and non-VPN based traffic is written to the TAP device setting the destination Ethernet address to the TAP device. The remaining configuration is identical to other members of the system as packets from the Internet will automatically have the clients IP as the destination as a product of the NAT. To provide for dynamic, self-configuring systems, VPN gateways announce their availability via an entry in the DHT. As future work, this approach can be explored to provide intelligent selection and load balancing of gateways.

4.5.2 The Client

VPN Clients wishing to use full tunnel must redirect their default traffic to their VN device. In our VPN model, we use a virtual IP address for the purpose of providing distributed VN services DHCP and DNS. This same address is used as the the default gateway's IP. Because this IP address never appears in a Internet bound packet, only its Ethernet address does, as shown in Figure 4-12, this approach enables the use of any and multiple remote gateways.

To support full tunnel mode, the VPN's state machine has to be slightly modified to handle outgoing packets destined for IP addresses outside of the VPN, only rejecting them when full tunnel client mode is disabled. When enabled, the VPN software sends packets to the remote peer acting as a full tunnel gateway. Likewise, incoming packets

that have a source address outside the subnet should not be rejected but instead the overlay address should be a certified VPN gateway prior to forwarding the packet.

To select a remote gateway, peers query the DHT. As there may be multiple gateways in the system, the peer randomly selects one, forwarding packets to that node. To ensure reliability, when the client has not heard from the gateway recently, the client sends a liveness query to the gateway. If the gateway is down, we take a pessimistic approach and find a new gateway when the next Internet packet arrives.

The real challenge in applying full tunnel VPN mode to P2P VPNs is the nature of the P2P system, namely dynamic connections. Peers do not know ahead of time what remote peer connections will be thus a simple rule switch does not work. Our original thought was to watch incoming connection requests and adding additional routing rules on demand, though this is only reasonably feasible with UDP as a TCP handshake message would need to be intercepted and potentially replayed by the local host in order to enable the rule and allow proper routing. The real drawback of the approach though is that UDP messages can easily be spoofed by remote peers enabling unsecured Internet packets to be leaked in the public environment. Even if the connections are secured, it could take some time for the peers to recognize a false connection attempt and delete the rule.

To solve the security problem, we propose an alternative, have all traffic directly routed to the VN device with no additional routing rules. The VN is then responsible for filtering P2P traffic and forwarding it to the LAN's gateway via Ethernet packets. In the VPN application, outgoing IP packets' source ports are compared to VPN application's source ports. Upon a match, the VPN application directs the packet to the LAN's gateway. The three steps involved in this process are 1) translating the source IP address to match the physical Ethernet's IP address, 2) encapsulating the IP packet in an Ethernet packet with a randomly source address [91] and the destination the LAN's gateway, and 3) sending the packet via the physical Ethernet device. Sending

an Ethernet packet is not trivial as Windows lacks support for this operation and most Unix systems require administrator privilege. Our platform independent solution uses a second TAP device bridged to the physical Ethernet device, allowing Ethernet packets to be sent indirectly through the Ethernet device via the TAP device. Because our solution results in incoming packets to arrive at a different IP address than the actual original source IP address TCP does not work in this solution. This method has been verified to work on both Linux and Windows using OS dependent TAP devices and bridge utilities.

4.5.3 Full Tunnel Overhead

While the full tunnel client method effectively resolves the lingering problem of ensuring that all packets in a full tunnel will be secure, it raises an issue: could the effect of having all packets traverse the VPN application be prohibitively expensive. Analysis of this approach compares it with one that uses the traditional routing rule switch. Figure 4.8 present the ping time from a residential location to one of Google's IP addresses using a gateway located at the University of Florida when the VPN is in split tunnel mode, full tunnel using the routing rule switch, and full tunnel using Ethernet forwarding. The results express that there is negligible difference between the full tunnel approaches. One interesting result is the latency to gateways public address in the routing test, which most likely is a result of the ping being sent insecurely avoiding the VPN stack completely.

4.6 Evaluation of VPN Network Configuration

This experiments explores bandwidth and latency in a distributed VPN system to motivate the usage of P2P links in a VPN. The VPNs used are include our prototype (IPOP), OpenVPN, and Hamachi. OpenVPN represents a typical centralized VPN, while Hamachi represents a well-tuned P2P-link VPN. The evaluation was performed on Amazon EC2 using small instance sized Ubuntu i386 instances to create various sized networks ranging from 1 to 32. OpenVPN uses an additional node as the central server and Hamachi has an upper bound of 16 due to limitations in the Linux version at the

time of this evaluation. To perform bandwidth tests, the instances are booted and query an NFS for the list virtual IP addresses, peers are ordered such that half the peers are act as clients and the other half the peers creating a 1 to 1 mapping between all sets. Latency and bandwidth tests are performed using netperf's request-reply and streaming tests respectively. Prior to the start of the tests, peers have no knowledge of each other, except the virtual IP addresses, thus connection startup costs are included in the test. Test are run for 10 minutes diluting the connection initiation overhead but represent an example of real usage. Results from the clients are polled at all locations and averaged together, though the OpenVPN server is measured separately. IPOP and OpenVPN use authenticated 128-bit AES, while Hamachi does not allow configuration of the security parameters and uses the default Hamachi settings.

Figure 4-14 and 4-15 present the results for latency and bandwidth respectively. Latency is measured in transactions of successful request/reply messages. In the latency test, it is obvious that having the central server increases the delay between the client and server and the results degrade more quickly as additional peers are added to the system. In small systems, OpenVPN shines probably due to optimized software, though as the system grows, the system bandwidth does not. By the time 8 peers have entered into the system, both decentralized approaches perform better than the OpenVPN solution. To summarize, decentralized VPN approaches provide better scalability, which can be immediately noticed by low latency times and, as the system grows, available bandwidth.

4.7 Evaluation of VPN Local Configuration

This section presents an evaluation of the different VN models, using prototype implementations built upon IPOP. The grid evaluation simulates a client/server environment and investigate CPU / networking overheads related with each approach. In addition a cloud deployment shows a proof of concept that connects multiple cloud and local resources as well as evaluation of overhead of the different approaches

in WAN and LAN environments. In all WAN experiments, a wide-area IPOP overlay network with approximately 500 overlay nodes distributed across the world on PlanetLab resources is used to bootstrap VN connections and to support DHT-based storage and P2P messaging.

The proposed VN models place varying demands on the resources of the systems involved. The evaluation focuses on CPU as experience suggest that this is the most significant limiting factor. As will be presented, the CPU load offered by these models depends on the bandwidth of the underlying network link, since a larger bandwidth requires more processing of packets. The tools for evaluating these VN models are, Netperf and SPECjbb, described in Appendix **??**.

4.7.1 On the Grid

The initial evaluation involves testing a client-server environment. The baseline hardware consisted of quad-core 2.3GHz 5140 Xeon with 5 GB memory and Gigabit network connectivity. Each VM was allocated 512 MB of RAM and ran Debian 4.0 using a Linux 2.6.25 kernel. The client side consisted of 4 VMs on 5 machines. The server side consisted of 5 VMs on one machine with 4 acting as servers and 1 acting as a gateway, which was necessary to control bandwidth into the system, done through the Linux utility **tc** [44], traffic control. In this environment, each server had 5 clients communicating with it. The setup is shown in Figure 4-16.

The evaluation results are presented in Figure 4-17 and 4-18. The maximum bandwidth of 600 Mbps is achieved when neither virtual network nor traffic shaping are enabled (“no spec.phys” at 1000 Mbps limit in Figure 4-17A), which is only 60% of the theoretical maximum. This limit is most likley the cost of VMMs, specifically the time required for a packet to traverse both VMMs networking stack as well as the hosts networking stack. Another observation was that transactions per second (Figure 4-18 B) do not improve significantly for **tc** bandwidth limit above 25 Mbps in all cases; thus we focus on the relevant data up to this limit.

Distinguishing features of the different VN models include the following. Figure 4-17A shows that bandwidth in all VN models is comparable with traffic control limit up to 75 Mbps. Beyond this point, the interface model achieves better bandwidth than the router model (VN processing is distributed across multiple processes); the spec/no spec ratio in the router model is smaller than in the interface model because there is less resource contention caused by VN processing on end nodes. For the same reason, the router tends to achieve better SPEC results (Figure 4-18A) than the interface. Figure 4-17B shows that the router performs poorly compared to the interface model in terms of transactions/second, though it achieves a better ratio of SPECjbb score (Figure 4-18B) to transactions than the interface at constrained bandwidths (less than 5 Mbps).

The hybrid method was tested, and results were nearly identical to those of the interface, from the point of view of the WAN part of the VN, it is the same architecture. These results are not reported in the plots as they add little value and further obfuscate the results.

The bandwidth cap observed in the router approach reflects the performance achieved by the current prototype of the router, subject to VM overheads. The use of VM is an assumption that is valid in the domain of cloud computing where all resources run in a VM. This experiment focused on the interplay between resource consumption by overlay routers and application performance. Optimized user-level overlay routers running on dedicated physical machines have been reported to achieve performance near Gbit/s in related work [88]; we expect that such cap can be raised substantially with improved VM handling of network packets and user-level router optimizations.

One thing that left unevaluated that may provide more interesting data would be providing the VN router dedicated hardware. In the test environments, this was infeasible, because all but one of the machines in the lab run VMware Server 1, which has a bug with setting the virtual network card in promiscuous mode. This effectively makes it impossible for a VM to be a VN router as no packets will ever make their

way into the VM, as the VMM will reject all packets. As such, the machines hosting the servers had VMware Server 2, which does allow setting a network interface into promiscuous mode.

4.7.2 In the Clouds

The goal of this experiment is to demonstrate the feasibility of connecting multiple cloud providers as well as local resources together through virtual networking. The sites chosen for evaluation were local resources at Universty of Florida and cloud resources provided by Amazon EC2 and GoGrid. A qualitative observation here was that the differences in the networking infrastructure exposed by different cloud providers reinforce the importance of the virtual network to allow flexibility in how end nodes are connected. Specific network configurations for the clouds were as follows:

- Amazon EC2 provides static IP networking (public and private), no Ethernet connectivity, and no ability to reconfigure IP addresses for network. Currently, only the VN interface model is supported.
- GoGrid provides 3 interfaces (one public, statically configured, and two private, which can be configured in any manner); the 2 private interfaces are on separate VLANs supporting Ethernet connectivity. The VN interface, router, and hybrid models are supported.

This experiment narrows down the performance evaluation to focus on WAN and LAN performance of VNs in cloud environments and consider Netperf single client-server interactions only. Amazon only supports Interface mode, thus it is only evaluated in the WAN experiment. It has been observed that, within Amazon, the VN is able to self-organize direct overlay connections [36]. Each test was run 5 times for 30 seconds, the standard deviation for all results was less than 1. Because of this, we only present the average in Table 4-4.

It can be seen in Table 4-4 that the VN adds little overhead in the Netperf-RR experiment. Between UF and GoGrid as well as between UF and Amazon EC2, the overhead for the Stream experiment was about 15%. This may be attributed to the additional per-packet overhead of the VN and the small MTU set for the VN interface (1200). The MTU, or maximum transmission unit, is the larget packet that is sent from an

interface. IPOP conservatively limits the VN MTU to 1200 down from the default 1500 to allow for overlay headers and to work properly with poorly configured routers, which we have encountered in practical deployments. A more dynamic MTU, which will improve performance, is left as future work. The EC2 / GoGrid experiment had greater overhead which could possibly be attributed to by the VM encapsulation of cloud resources.

Table 4-5 shows that some of our performance expectations for the different models in a LAN were accurately predicted while others were not so clear. Stream results match the expectation that VN models hybrid and router bypass virtualization and get near physical speeds, whereas interface does not. Interestingly, RR had rather poor results for Router and Hybrid though further testing seems to indicate that this is an issue of using the VLAN connected network interfaces as opposed to the public network connected interface.

4.8 Figures and Tables

IPOP	Structured P2P overlay with O(Log N) routing hops, where N is th
N2N	Unstructured P2P network, super nodes
OCALA	Not tied to any sp
SoftUDC VNET	Decentralized with
ViNe	ViNe authority configures global network descriptor table (GNDT) explici
Violin	Decentralized network v
Virtuoso VNET	Decentralized with

Table 4-1. Virtual Network Comparison

Table 4-2. VPN Classifications

Type	
Centralized	Clients c
Centralized Servers / P2P Clients	Servers provide authentication, session management
Decentralized Servers and Clients	No distinction between clients and servers; each
Unstructured P2P	No distinction between clients and serv
Structured P2P	No distinction between clients and servers; members

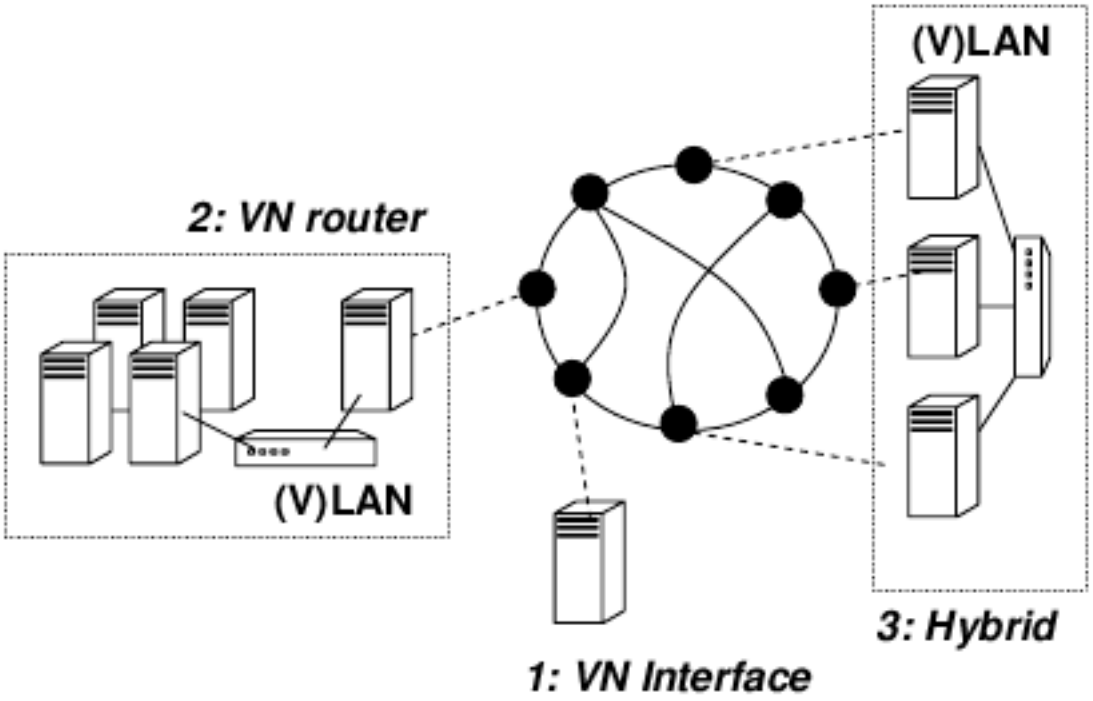


Figure 4-1. Illustration of the three different deployment models considered in this paper. In VN interface mode (1), each node has an overlay ID and communicates to all other nodes through VN tunneling. In VN router mode (2), only the router has an overlay ID and routes for a set of resources; LAN communication does not require VN tunneling. In hybrid mode (3), each host has an overlay ID; LAN communication does not require VN tunneling.

	Interface	Router
Host LAN	No assumption	Ideally, VLAN
Host software	IPOP, tap	End node: none. Router: IPOP, tap, bridge
Host overhead	CPU, memory	End node: none. Router: CPU, memory
LAN traffic	Through IPOP	
Migration	Handled by node	Involves source and target routers
Tolerance to faults	Nodes are independent	Router fault affects all LAN nodes

Table 4-3. Qualitative comparison of the three deployment models

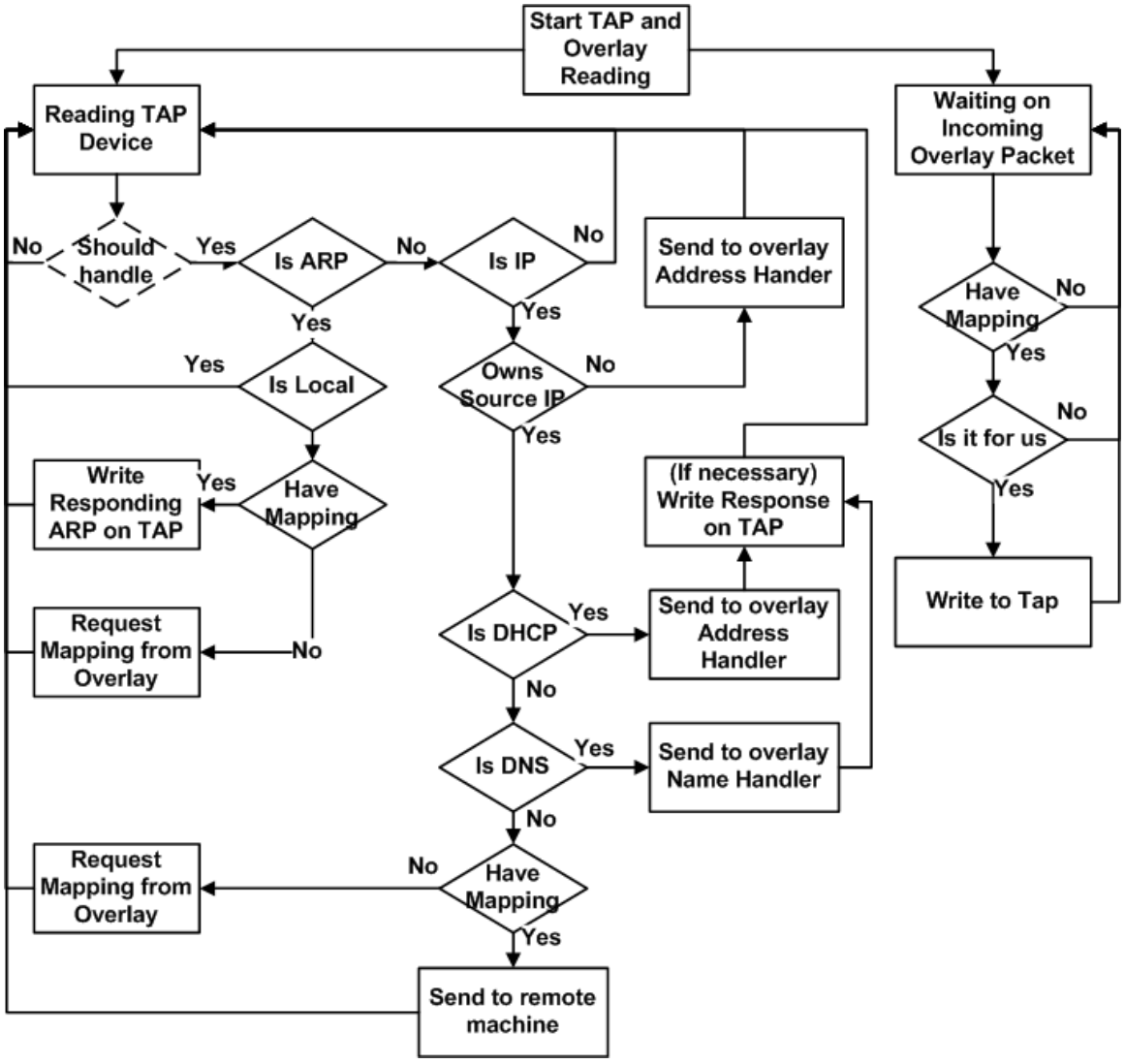


Figure 4-2. The state diagram of a self-configuring VN. In this model, a VN interface is identical to a VN router with the caveat that the TAP device is not bridged, thus isolating the VN traffic. The “Should Handle” with dashed lines is a feature that is specific to the VN hybrid; that is, a VN hybrid must be configured to communicate for a single network device.

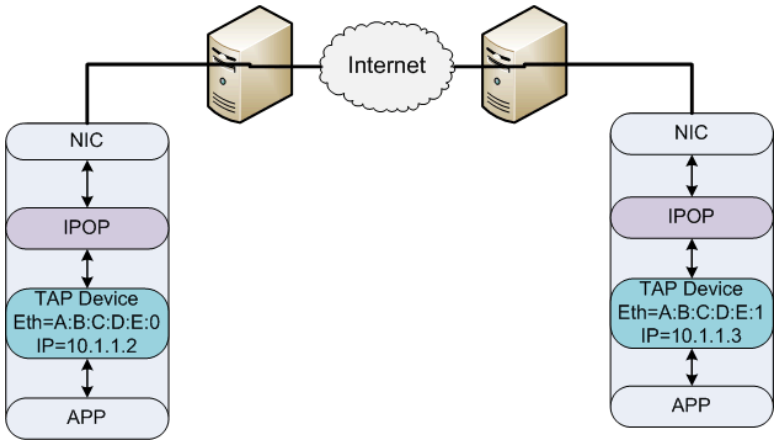


Figure 4-3. A VN deployed as an interface for single machine usage. The user of the machine is presented two interfaces on two different IP subnets. All non-VN subnet based traffic is routed normally via the default interface.

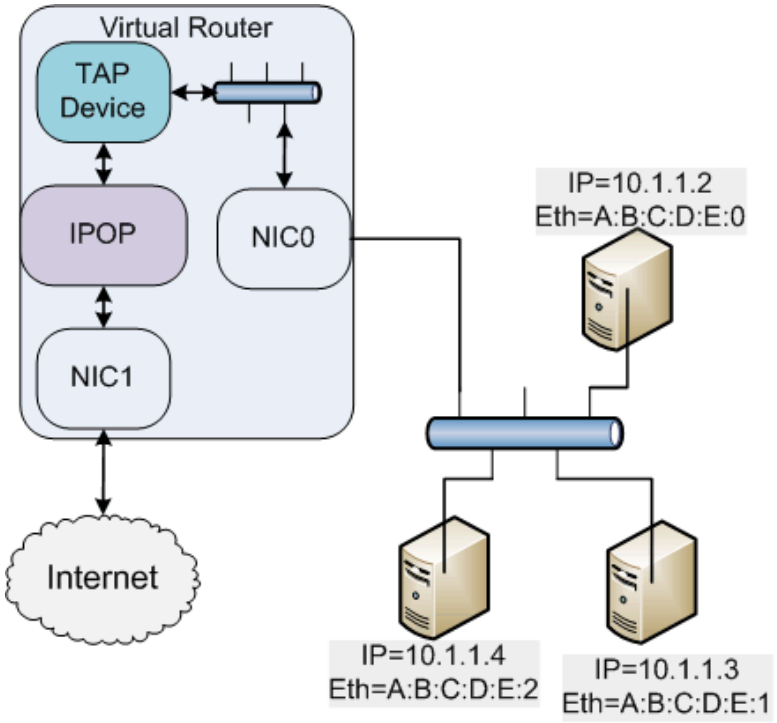


Figure 4-4. A VN deployed as a router providing virtual network access for an entire layer 2 network. Each machine in the network only has a VN-based address, though they can communicate directly with each other (and with proper routing rules and NAT setup the Internet as well). The machine hosting the VN can also have an IP address in the network by assigning one to the bridge.

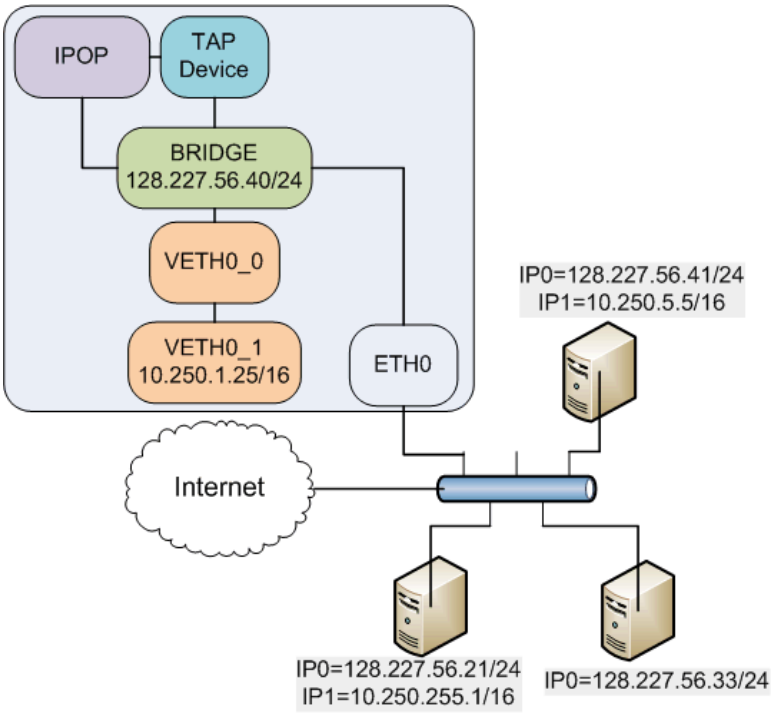


Figure 4-5. A VN deployed in a hybrid mode providing virtual network access for a single machine but bypassing the VN when a VN peer is local. This model is similar to having two network cards from a single machine going to one switch. The key feature is that this model allows a machine to be in multiple IP address space subnets and have layer 2 traffic as well.

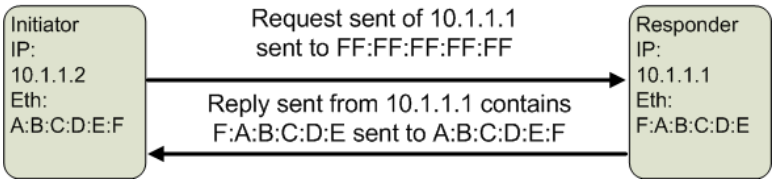


Figure 4-6. ARP Request/Reply Interaction.

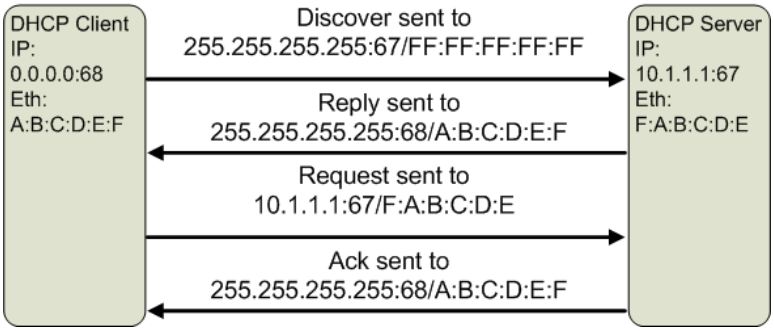


Figure 4-7. DHCP Client/Server Interaction.

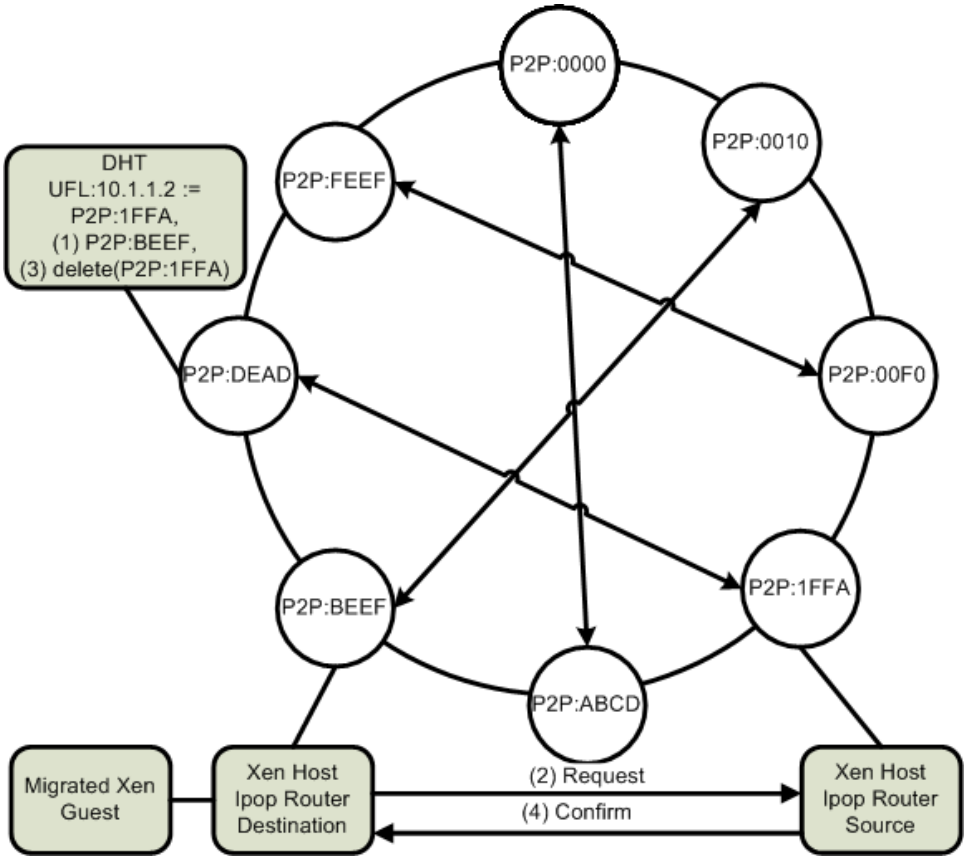


Figure 4-8. The VN operations that occur after a guest (VM) has been migrated. (1) The destination retrieves the P2P information of the source from the DHT and optimistically places its information into the Dht. (2) The destination requests that the source delete its information from the DHT. (3) The source confirms that the VM is no longer present and performs the delete. (4) The source notifies the destination that its request has finished successfully.

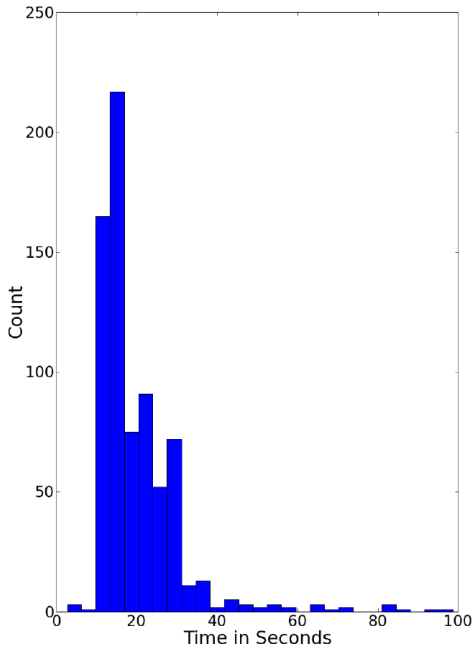


Figure 4-9. VN Router migration evaluation. Over 50 different IPs migrated about 10 times each. The average was 20.11 seconds with a standard deviation of 10.89. In this experiment, the majority of this time comes from VN migration, whereas VM migration requires less than a second.

Figure 4-10. Comparison of IP Broadcast and Multicast using overlay Broadcast and Unicast.

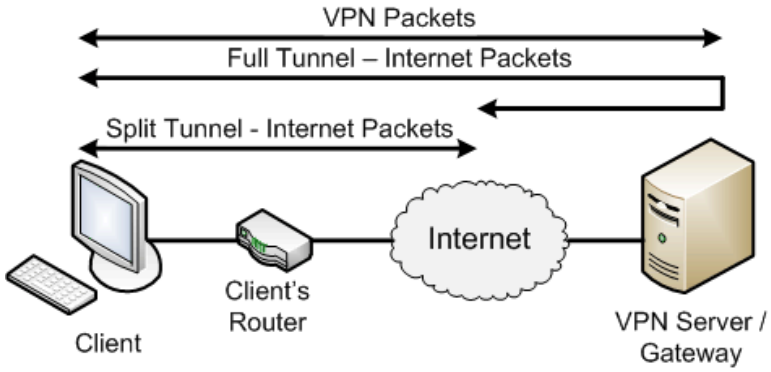


Figure 4-11. An example of both full and split tunnel VPN modes. In both, packets for the server are sent directly to the server. In split tunnel mode, Internet packets bypass the VPN and are routed directly to the Internet. In full tunnel mode, Internet packets are first routed to the VPN gateway, and then to their Internet destination.

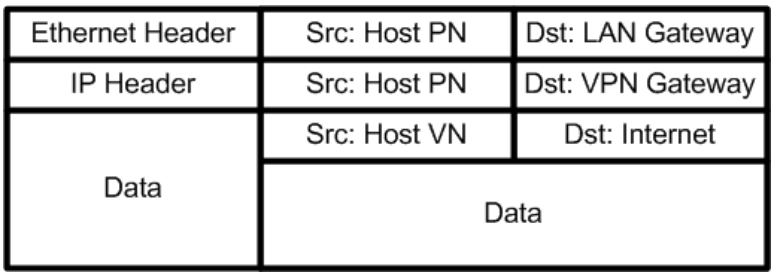


Figure 4-12. The contents of a full tunnel Ethernet packet. PN and VN are defined as physical and virtual network, respectively.

	Google	GW Pri	GW Pub
Ethernet	70.6	12.9	13.9
Routing	71.4	13.2	11.0
None	66.1	N/A	10.9

Figure 4-13. Latency results comparing full tunnel approaches measured in ms. Legend: GW Pri - gateway's VPN address, GW Pub - gateway's VPN address, Ethernet - full tunnel Ethernet packet method, Routing - full tunnel routing rule switch, None - split tunnel or no VPN.

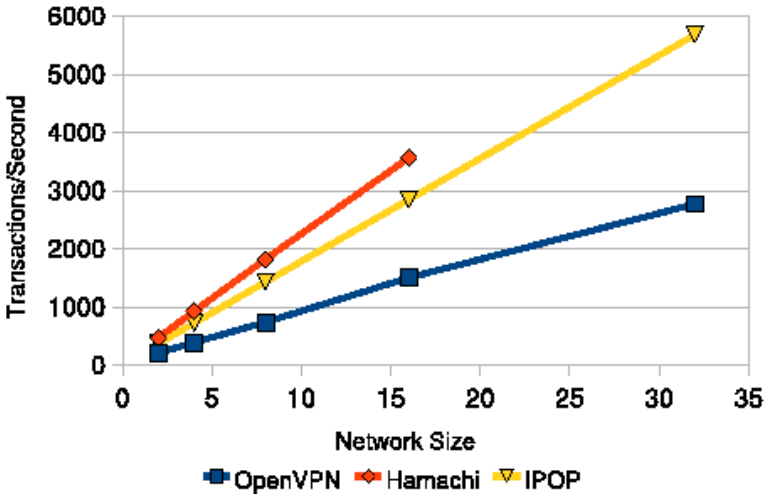


Figure 4-14. System transaction rate for various VPN approaches.

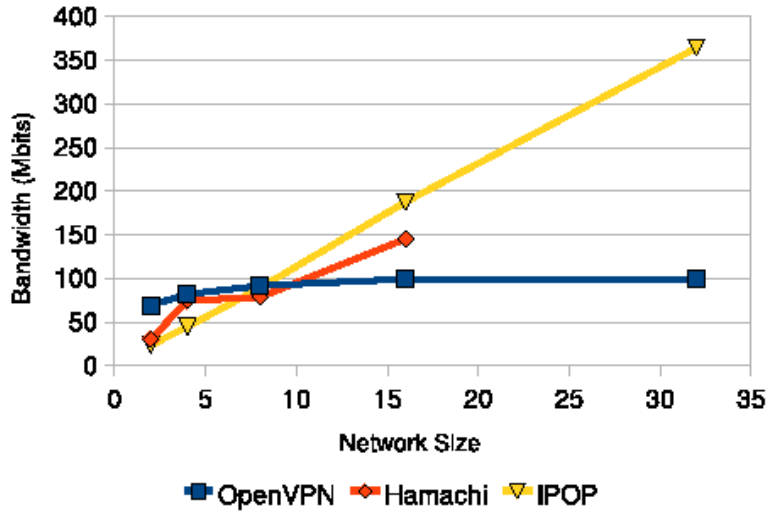


Figure 4-15. System bandwidth for various VPN approaches.

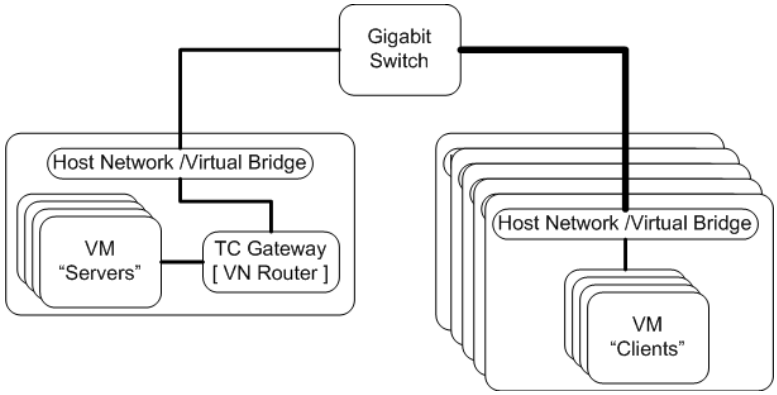
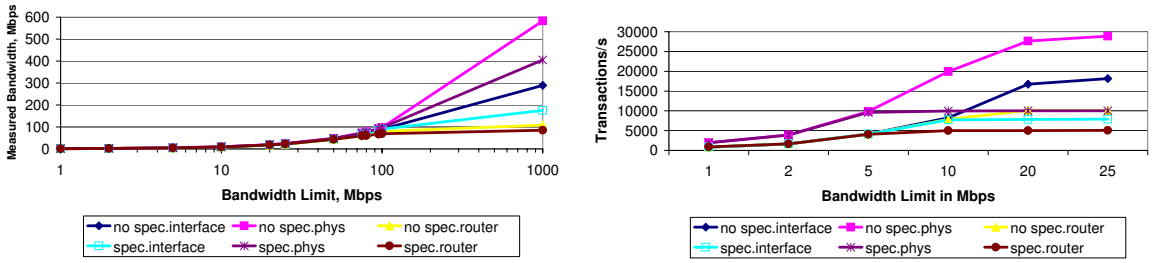


Figure 4-16. The system setup for the grid experiments. The VM “Servers” ran SPECjbb and were also the site for the collection of the netperf benchmarks. All the VM “Servers” were connected through the TC Gateway through host-only networking to the VM “Clients”. All traffic for the VM “Servers” passes through the TC Gateway, which also doubled as the Router in the Router experiments.



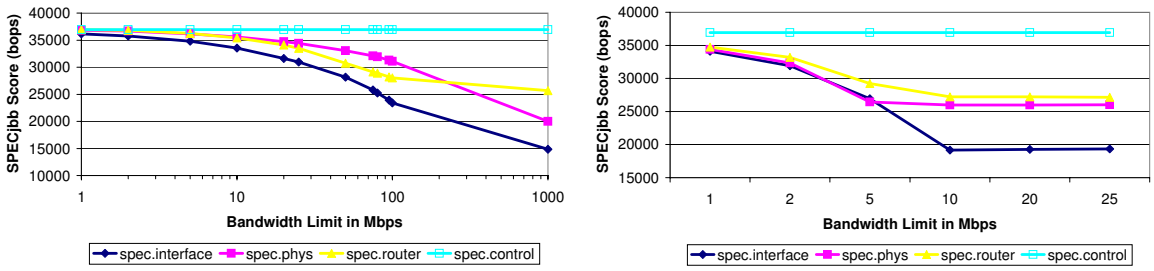
A TCP Stream bandwidth, SPECJbb load

B TCP RR latency, SPECJbb load

Figure 4-17. Netperf measurements with and without SPECjbb load. Lines are of the form (no spec, spec).(phys, interface, router). Where “spec” indicates SPECjbb benchmark is active, while “no spec” indicates that SPECJbb is inactive. “phys” implies the absence of IPOP with benchmarks occurring directly over the “physical” network card. “interface” and “router” present the results for VN interface and router models respectively.

	EC2 / UF	EC2 / GoGrid	UF / GoGrid
Stream Phys	89.21	35.93	30.17
Stream VN	75.31	19.21	25.65
RR Phys	13.35	11.09	9.97
RR VN	13.33	10.69	9.76

Table 4-4. WAN Results for inter-cloud networking. Stream is in Mbs and RR is in trans/s (The inverse of trans/s would be equal to the average latency).



A SPECJbb score, TCP Stream load

B SPECJbb score, TCP RR load

Figure 4-18. SPECjbb scores with and without Netperf load. Lines are of the form spec.(control, phys, interface, router). “spec” implies that SPECJbb executes in all tests. In “control” Netperf is inactive, that is, it is the maximum attainable value for SPECJbb. “phys” implies the absence of IPOP with benchmarks occurring directly over the “physical” network card. “interface” and “router” present the results for VN interface and router models respectively.

	VN Interface	VN Router	VN Hybrid	Physical
Stream	109	325	324	327
RR	1863	2277	2253	3121

Table 4-5. LAN results performed at GoGrid. Stream is in Mbs and RR is in trans/s. Interface and Physical used the eth0 NIC, while Router and Hybrid used eth1. Different VLANs may give different results.

CHAPTER 5
GRID APPLIANCE

High throughput computing (HTC) is a form of opportunistic computing that, unlike high performance computing (HPC) seeking only powerful resources, benefits from ad-hoc, arbitrary resources including computers found in computer labs, homes, and offices as well as cloud resources and retired HPC clusters. Creating and maintaining HTC systems that cross administrative domains (grids) require expertise in networks, operating systems, and grid middleware to configure the sites uniformly and guarantee connectivity amongst sites involved.

Administrators each have their own way of configuring resources and may be hesitant or unwilling to configure resources in a way that conflicts with the environmental norm. This conflicts with the requirements of merging resources across administrative domains as computing resources are typically configured uniformly having a common environment and network rules. Administrators would prefer not having exceptional rules for a subset of resources under their domain and do not want to grant access to lesser known, remote users. Network constraints such as firewalls and network address translation (NAT) can prevent cross-domain communication. With exceptions this may be ameliorated, but additional rules may be required for each new cluster or resource added to the cross-domain grid.

HTC clusters are not limited to large systems requiring dedicated administrators: there are many systems that discuss the use of desktop or opportunistic grids, such as Boinc [**?**] and PVC [74]. While Boinc solutions may be easily configured, the approach relies on a centralized scheduler and that applications be compiled using Boinc API. While PVC enables parallel tasks and more decentralized system configuration, the approach has scalability concerns and relies on a centralized node to assist in node connectivity. In general, there exists no solution that provides scalable, self-configuring, decentralized grid systems for non-experts.

Connecting resources distributed across the Internet can be challenging due to limit of IP (Internet Protocol) addresses available to an organization. NAT further complicates the issue by limiting the formation of direct links between remote sites without external assistance. When creating HTC systems across a small set of institutions, approaches that use Internet Service Provider VPNs, Layer 2 Tunneling Protocol (L2TP) VPNs, and other user-configured VPN approaches can be used. Most solutions require some form of centralization and static links; as systems expand dynamically, the manual configuration of the system grows significantly. VPNs do, however, provide means of securing the system and, through the use of proper middleware, can allow users to interact with each others resources without additional configuration from the local site administrator.

The Archer project [34], a collaborative academic environment linking institutions and external users for the purpose of computer architecture research, is an example of a real system having the described constraints. Many researchers have a need for resources occasionally and rather than investing in a large pool of dedicated resources for a single institution they are able to pool their resources together using HTC mechanisms. The resulting system allows individuals the opportunity to complete their jobs quickly and ensure that their resource contribution is not idle when locally unused. This use case potentially introduces a new issue where the users may not be experts nor have the ability to include an expert in the construction of the system.

Explicitly the requirements for a system in these environments are: 1) users should be able to easily add and remove resources, 2) resources should not require configuration to allow remote users access, 3) tasks that run inside the grid should not have access to external resources, 4) external resources should not be able to access the grid, 5) resource priority should be granted to the resource's owner, and 6) malicious users should be able to be removed. This chapter describes an approach to handling these requirements to enable the creation of a dynamic, decentralized HTC grid through

a novel approach involving decentralized overlays enabling a self-configuring VPN and HTC environment.

In previous work, IPOP [35] was bundled with other grid middleware into a virtual machine called the Grid Appliance [**?**] for easy to use decentralized virtual networking. The approach was highly couple, and while it made it easy to connect to existing grids to add or access resources, it required expertise for users to create and manage their own independent grids. This paper extends that work to enable non-experts to create and manage their own grids through a group-oriented model embodied in a web 2.0 infrastructure providing a public key infrastructure along with VPN and grid configuration. The approach describes methods that can be used to easily configure and combine resources from virtual, physical, and cloud environments.

5.1 Task Schedulers

The most fundamental requirement of a cluster is the task scheduler. Each task scheduler has a general focus and selecting one that works well in a specific environment can make the configuration of the system significantly easier. Generally, there are three approaches to configure HTC clusters: 1) task workers pull from a centralized manager as employed by Boinc [**?**], 2) task workers receive jobs from a centralized submission site, and 3) task workers receive jobs from any member of the HTC infrastructure. Both 2 and 3 can be implemented using a myriad of different job schedulers with verifying levels of difficulty. Task schedulers supporting this behavior include Condor [57], Sun Grid Engine, and PBS and its relative Torque.

Unlike other task schedulers, Condor supports decentralized users supported by having separate components that keep track of resources and negotiates resource allocation from those that make the resource requests and submit tasks. This abstraction allows for a simple centralized system to maintain the grid without requiring any run-time configuration. In addition, Condor allows open unauthenticated access to the grid as long as a peer is within a subnet. Using a VPN ensures that that only members of the

VPN have access to grid resources. To enable this behavior in other grid schedulers would require modification or additional middleware, like Globus [12]. Other reasons motivating the use of Condor include it being open source, having an active community, and focus on opportunistic cycles. In the list of requirements, Condor also handles the ability to assign groups or institutions privilege on their own resources when shared in a collaborative environment. Condor supports multiple, decentralized negotiators through flocking.

Though settling on a task scheduler, it is important to present a comparison of other features provided by task schedulers, as illustrated in Table 5-1. Experience dictates that the approach that requires the least amount of work to obtain the most amount of features is ideal. The important takeaway from manuals and experimental configuration of various environments was that Condor can easily be configured to provide a P2P-like scheduling environment, whereas other approaches were heavily centralized. While they could be decentralized and each had their own benefits that it did not outweigh the ease of use provided by Condor.

5.2 P2P VPNs

Many of the requirements described can be addressed through the use of a VPN. A VPN can assist in dealing with connecting network constrained resources, securing the grid from the outside world, and removing malicious forces inside. Grid computing has seen its fair share of VPNs such as ViNe [87], Violin [46], and VNET [85]. These approaches are limited by their lack of self-configuration, namely that static links between peers must be created, security credentials must be manually distributed, and lack of support for direct connectivity between NAT and firewalled peers without additional configuration from the user limiting their applicability for such resources to communicate with each other through proxy servers. In PVC [74], the authors describe an approach that self-configures through a centralized server with NAT traversal support, which works on many NAT devices but only when used without a stateful firewall. The

drawbacks with this approach are the centralized key distribution center (KDC) and lack of encrypted links.

IPOP [35] provides a P2P virtual network with decentralized and self-configuring link creation with NAT traversal support that works with most NATs using a distributed hash table (DHT) for address allocation and resolution. Previous approaches [**?**] used IPsec for security or went without it entirely as IPOP lacked the ability to secure links. Chapter [**?**] presents GroupVPN, which transforms IPOP into an automated VPN with enhanced NAT handling through the use of decentralized relays (proxies), enabling two-hop, low latency connections when NAT and firewall traversal fails.

The authentication system employs a public key infrastructure (PKI), made accessible through a group-based Web 2.0 environment. Users can create and join groups, and group owners can grant user access, promote users to administrative capabilities, or remove users who have overstayed their welcome. A PKI has a very natural P2P aspect, in that, peers can mutually authenticate each other by verifying signatures on the exchanged certificates unlike the centralized authentication such as a KDC. To automatically configure the system, users download a GroupVPN configuration file through the group website, which can be provided to the GroupVPN by command-line or GUI. The next time GroupVPN is started, it will use this configuration to automatically obtain a signed certificate by sending a certificate request along with a shared secret contained in the configuration to the group server through HTTPS, uniquely authenticates the user. If the user has appropriate permissions, the server will sign the certificate request. To remove peers, the system supports a reliable, centralized user revocation list located at the group website and decentralized revocation by broadcast and distributed data stores.

5.3 GroupAppliances

An appliance is defined as a dedicated, blackbox device requiring little if any configuration from the user. While traditional computing appliances like a router, network

storage, or even cluster resources have been available as hardware appliances, the recent resurgence of virtualization initiated by VMware and Xen has made software appliances by means of virtual appliances popular. Recently, cloud computing has become popular in large part thanks to Amazon's EC2. Both virtual and cloud resources present themselves as cheap computing for HTC and opportunistic computing purposes, because they can be setup in such a way as to have no or limited effect on users' computers and can be shutdown when no longer in use. Even with virtual and cloud appliances available to tap into these resources, they still require some manual manual configuration to form a grid, and these packaged solutions cannot easily be applied to hardware resources.

Our solution is the creation of a generic software stack that self-configures based upon a user input configuration file. The contents of a configuration file are the type of resource (dedicated compute node, job scheduling node, a mixture of the two, or the job negotiating central server); the user's group and username on the site; and the grid's GroupVPN configuration data. The configuration file is generated from a Web 2.0 group-based infrastructure called GroupAppliance, using a single GroupVPN group to connect all members of the grid together in a VPN but using the GroupAppliance group to distinguish their resource contributions. Thus many GroupAppliances groups can be linked together through a GroupVPN group. By distinguishing resource contributions, users are able to get credit and gain priority to their resources when submitting tasks to run.

When a user downloads the configuration file from the GroupAppliance infrastructure, the data is stored in a floppy disk image that can be used on physical resources by writing the image to a real floppy disk or to a USB drive, a VM by adding a virtual disk image to the VM, and clouds through instance specific configuration data. EC2 provides per-cloud instance configuration in a parameter called "user data" providing up to 16 KB of data available only to that cloud instance. At the time of this writing, it appears that

EC2 is the only cloud provider to offer this option. Alternatively, users could configure an image specifically to run for this cloud by inserting the floppy image into the cloud image and then generating cloud instances from this new image, or the user could setup a storage cloud where the cloud instances could retrieve the floppy. Because the floppy contains private GroupVPN configuration data it should not stored on public resources.

Upon booting, the grid configuration scripts parse the floppy to determine how to configure the machine. Negotiators insert an ad into the DHT, whereas resources and task submitters query the DHT for the list of negotiators, selecting one and relegating the rest for flocking. At which point, tasks can be submitted and run.

5.4 Constructing Environments

Often VMs are favored for the distribution of complicated applications as experts can configure them and release the results as a complete working system. This approach may limit non-expert use to the VM appliance, which may be undesirable for users that want to configure their own systems without reuse of the existing VM. Guides may exist for the creation of systems, most systems are too complex for non-experts to produce similar results found in the VM. In addition to supplying VMs, providing packages (DEB and RPM) enable easy installation in arbitrary environments and through the use of package managers (APT and YUM) handle configuration such that the requirements listed in the introduction are handled. Packages can be provided that automatically install and configure the task scheduling middleware and a VPN as well as sandbox the environment, limiting users network access to the virtual network and not external networks such as other local resources and the Internet. The remaining components are configurable through the GroupAppliances interface and decentralized through the DHT.

The most important components in securing an environment are limiting internal and external access from inside the system. Specifically, internal resources have no password enabled accounts to avoid cases where users submit tasks that attempt to

provide more privileged access to the user. In the event that a passworded account is necessary, such as on a client machine, the system is configured to prevent permission switching by the task scheduler user, in Linux, for example, this is done by limiting *su* access. By default, Condor runs jobs as either nobody or the user named “Condor”. This limits access to many of the core components of the system already, but it does not limit the users ability to read files that allow reading from anyone on the system and the ability to communicate to external resources from inside the machine. The user data directory is made readable by only the user and group who own the files and directories preventing remote users from reading local user personal data. Limiting access to external resources has been implemented by a firewalling, allowing the Condor user to only have the ability to send packets over the virtual network.

Job submission nodes have an additional consideration emphasizing user-friendliness. To do this, file system access through NFS and Samba as well as remote access through SSH are enabled to allow users on the same host can access the resources without having to configure additional utilities or using the VMs interface. To prevent access through the virtual network or Internet for security purposes, a second network card connects the system to a host-only interface. By binding all user applications to use the network interface, they do not require extra security enhancements. Alternatively, applications like SSH could be enabled to only allow private key based login. In general, only dedicated compute nodes and possibly the job negotiator will run on physical or cloud resources, whereas clients will most likely exclusively use VMs.

preparing the system is straight-forward: users configure the package manager to link to a package distribution site and then install the desired packages for the grid resource. When finished, the user can restart the device or restart the grid service with the floppy image adding a new resource to the grid. The VPN will acquire a signed certificate and grid configuration scripts will configure Condor and other services through interaction with the DHT.

5.5 Related Work

There are many projects that seek to provide easy to use resources for HTC and opportunistic computing. We focus on two approaches whose focus is user-friendly dynamic grids: PVC [74] and GPU [**?**].

PVC or Private Virtual Clusters creates instant grids using a PVC specific virtual network and task scheduler as well as VMs to isolate remote jobs from users' resources. Resources discover and TCP NAT traversal are performed through a centralized system broker, though it is unclear how the resources are configured with the knowledge of the broker, nor how a broker is configured. Loss of the broker can prevent usability of the system. PVC virtual network lacks privacy, links are authenticated through a KDC but messages are not encrypted or authenticated. PVC scalability constraints are unclear, as experiments were limited to 8 nodes. In contrast, our approach focuses on privacy, scalability, and self-configuration through a decentralized system.

GPU or Global Processing Unit uses the Gnutella P2P system to create a completely decentralized computing grid. The authors state that the expected size for grids range from 5 to 15 nodes. While the authors do not mention NAT traversal, there are many Gnutella systems that do support various forms of it. There is no mention of providing safety to the users' resources from malicious tasks. While GPU provides easy configuration, it lacks the ability to run jobs in a sandbox and support large pools of resources.

There are many other desktop grid environments that use Boinc as the underlying method to push jobs. As explained earlier, Boinc uses a few approaches that are undesirable for our requirements with the primary issue that Boinc job scheduling is heavily centralized. In addition, for Boinc systems that allow running arbitrary applications, it is unclear how secure they are.

5.6 Evaluation

This evaluation evaluates the validity of this approach by evaluating the time time required to create and utilize a grid consisting of various distributed resources using a reference implementation of the system described in this paper. Using VMware resources behind a Cisco and “iptables” NAT at the University of Florida (UF), KVM resources behind an “iptables” and KVM NAT at Northeastern University (NEU), and cloud resources provided by EC2, pools of 50 resources from each site were booted independently and then together, resulting in 4 different test runs. The resources connect to an existing pool consisting of a negotiator and client node. Once all the resources have connected, the client submits a job to each resource. Three timespans are measured: “start” - begins with starting the experiment including the copying of files and creation of instances until all resources have been powered on, “connect” - begins with “start” though ends when all resources appear in “condor_status” and includes start time, and run - time from the submission to the conclusion of a 5 minute job to all resources Like connect, run measures the time for VPN connections, only from the client to the resources instead of from the negotiator. All tasks are automated through scripts with human interaction required only to start the events of grid boot and job submission. Results are presented in Figure 5-2.

As the systems consist of various hardware and software configurations, the time to start is provided as a basis for the remaining numbers. Some of the interesting experiences of the experiment were: 1) the combination of the “iptables” and VMware NAT was more easily traversable than the combination of “iptables” and KVM NAT and 2) in the experiment consisting of 150 peers, nodes were actually well connected much earlier, but due to missed packets and Condor timeouts, not all resources were accounted for in Condor as early as in the other tests.

5.7 Real Use Cases

There are several deployments using the system described. Over the past 2 years, I have been student lead in an active grid deployed for computer architecture research, Archer [34]. Archer currently spans four universities with 500 resources, we have had hundreds of students and researchers submitting jobs with over 150,000 hours of total job execution in the past year alone. Groups at the Universities of Florida, Clemson, Arkansas, and Northwestern Switzerland have used it as a tool to teach grid computing. Purdue is constructing a large campus grid using GroupVPN to connect resources together. Recently, a grid at La Jolla Institute for Allergy and Immunology went live with minimal communication with us.

Table 5-1. Task scheduler comparison

	50 - EC2	50 - NEU	50 - UF	150 - All
Start	2:44	10:21	20:23	21:14
Connect	5:10	21:47	24:16	38:27
Run	7:15	6:35	5:53	21.19

Table 5-2. Time in minutes:seconds to start and connect resources to an existing grid and run jobs from.

CHAPTER 6
SOCIAL PROFILE OVERLAYS

Online social networking has become pervasive in daily life, though as social networks grow so does the wealth of personal information that they store. Once information has been released on a social network, known as a user's profile, the data and the user are at the mercy of the terms dictated by the social network infrastructure, which today is typically third-party, centrally owned. If the social network engages in activities disagreeable to the user, due to change of terms or opt-out programs not well understood by users such as recent issues with Facebook's Beacon program [66], the options presented to the user are limited: to leave the social network (surrendering their identity and features provided by the social network), to accept the disagreeable activities, or to petition and hope that the social network changes its behavior.

As the use of social networking expands to become the primary way in which users communicate and express their identity amongst their peers, the users become more dependent on the policies of social network infrastructure owners. Recent work [14] explores the coupling between social networks and P2P systems as a means to return ownership to the users, noting that a social network made up of social links is inherently a P2P system with the aside that they are currently developed on top of centralized systems. In this paper, we extend this idea with focus on the topic of topology; that is, how to self-organize social profiles that leverage the benefits offered by a structured P2P overlay abstraction.

Structured P2P overlays provide a scalable, resilient, and self-managing platform for distributed applications. Structured overlays enable users to easily create their own decentralized systems for the purpose of data sharing, interactive activities, and other networking-enabled activities. This work extends Private Virtual Overlays described in Chapter 3. This chapter expands upon this approach with in-depth discussion on how to apply this technique to enable social network overlay profiles.

Social networks consist of users, each has a profile, a set of friends, and private messaging. The profile contains user's personal information, status updates, and public conversations, similar to a message board. Friends are individuals trusted sufficiently by a user to view the user's profile. Private messaging enables sending messages discretely between users without leaking the message to other members. Using this model, we describe how a public overlay can be used as a directory for finding friends and joining existing profile overlays. Each user has their own profile overlay, secured via a public key infrastructure (PKI) to which they are the certificate authority (CA). The profile overlay stores profile data in its distributed data store, supporting profile access in scalable mechanisms regardless of the profile owner's online status. This chapter explains architecture of these overlays, presented in Figure 6-1, how they are used to find and befriend peers, and describes approaches to handling profile data and establishing initial connections to profile overlays.

6.1 Peer-to-Peer Social Networks

In [15], a DHT provides the look-up service for storing meta data pertaining to a peer's profile. Peers query the DHT for updated content from their friends by hashing their unique identifiers (e.g. friends' email addresses). The retrieved meta data contains information for obtaining the profile data such as IP address and file version. Their work relies on a PKI system that provides identification, encryption, and access control. In contrast, our approach provides each user their own private overlay secured by point-to-point encryption and authentication amongst all peers in the profile overlay. The profile overlay provides a clean abstraction of access control, whereby once admitted to a private overlay, users can access a distributed data store which holds the contents of the owners profile.

[80] takes a different approach by depending on virtual individual servers (VIS) hosted on a cloud infrastructure such as Amazon EC2. Friends contact each other's VIS directly for updates. A DHT is used as a directory for groups and interest-based

searches. Their approach assumes bidirectional end-to-end connectivity between each VIS, where a profile is only available during the up time of the VIS. Because of the demands on network connectivity and up time, the approach assumes a cloud-hosted VIS and has difficulty being used on user-owned resources. Our approach enables users to avoid the need for all-to-all connectivity and constant up time through the use of NAT traversal support and the ability to store the profile in the overlay's distributed data store.

The approach presented in [23] also uses a DHT for looking up a peer's circle of friends. Once a node in the peer's outermost circle is found, that node is used to route profile requests to the innermost circle which contains replicas of a peer's profile. Trust is enabled through the use of an identification service contacted through the DHT. The circle of friends concept lacks the simplicity of the abstraction made in our approach, which can easily be applied to existing structured overlays unlike the concept of innermost and outermost circles. Our approach also enables the profile owner to serve as a CA, ensuring that nodes can only access a profile overlay after having obtained a signed certificate.

Unlike the above approaches, the P2P social network presented in [9] uses an unstructured overlay without a DHT where peers connect directly to each other rather than through the overlay establishing unique identifiers to deal with dynamic IPs. Peers cache each other's data to improve availability. While helper nodes are used to assist with communication between peers behind NATs. The approach lacks security and access control considerations and lacks the guarantees and the simplicity of the abstraction offered by a structured overlay.

6.2 Social Overlays

In this section, we explain how to map online social networking to our multi-overlay social network consisting of a public directory overlay with many private profile overlays. The directory overlay supports friend discovery and verification and stores a lists of

peers currently active in each profile overlay. Profile overlays support message boards, private messages, and media sharing.

6.2.1 Finding and Verifying Friends

In a traditional social network, a directory provides the ability to search for users using public information, such as the user's full name, user ID, e-mail address, group affiliations, and friends. The search results return zero or more matching directory entries. Based upon the results, the user, *A*, can potentially make a friendship request. The request receiver, *B*, can review the public information of A to making a decision. If *B* accepts the request, *A* and *B* are given access to each other's profiles. Once profile access has been enabled, the users can learn more information, and if it turns out to be a mistake, the peers can unilaterally end the relationship.

To map this to our proposed social overlay, the directory entries would be inserted into the DHT of a public overlay. As discussed in previous work, the DHT keys for these entries should consist of a subset of the user's public information in lower-case format and hashed to an overlay address. The value stored at these keys is the user's certificate, which consists of its public information and an overlay address where the user expects to receive notifications. This overlay address can be used for asynchronous offline messaging, whose function we will explain shortly.

Because the users need a way to verify each other that involves social credentials, we propose the use of a new form of certificate. The main portion of the certificate is similar to a self-signed x509 certificate with public information such as user's name, e-mail address, and group affiliations embedded into the certificate. At the tail of the certificate is a friend list represented by many friend entries. To do this we propose employing a technique similar to PGP: users can acquire from their friends a signed message consisting of a hash of the peer's certificate, the time stamp, and the friend's certificate hash signed by the friend. Since PGP does not provide a strong method for revocation, the time stamp provides additional information to help decide whether or not

a friendship link is still active without accessing the profile overlay of either peers. Peers should request a new friend list entry within a certain period of time or it will appear that the friendship is no longer valid.

While looking for an individual, a peer may discover that many individuals have overlapping public information components, such as the user's name. Assuming all entries are legitimate, the overlay must have some method of supporting multiple, distinct values at the same key, leaving the peer or the peer's DHT client to parse the responses and determining the best match by reviewing the contents of each certificate. Alternatively, a technique like Sword [10], which supports distributing the data across a set of nodes and using a bounded broadcast to discover peers that match all information, could be used for searching.

If a peer, *A*, desires a friendship with another peer, *B*, *A* issues a friendship request, which will be stored in the DHT at the overlay address listed in *B*'s certificate, as described earlier. The friendship request consists of the self-signed certificate of *A*, the requesting peer; the public information of the request receiver, *B*; and a time stamp; all signed with the private key associated with *A*'s private key matched to their self-signed certificate.

Within a reasonable amount of time after a request has been inserted into the DHT, *B* can come online and check for outstanding requests. Upon receiving a request, *B* has three choices: a conditional accept, an unconditional accept, or a reject. During an unconditional accept, *B* signs *A*'s request and issues a request to befriend *A*. Alternatively in the case of a conditional accept, *B* issues a friendship request, waits for a reply, and investigates the profile prior to signing the *A*'s request. Once a user has received a signed certificate, they may access the remote peer's profile overlay as discussed in 6.2.2, which is also responsible for activities such as revocation.

6.2.2 The Profile Overlay

In a traditional social network, the profile or user-centric portion consists of private messaging, data sharing, friendship maintenance, and a public message board for status updates or public messages. In this section, we explain how these components can be applied to a structured overlay dedicated to an individual profile.

Using the techniques such as those described in [90], it is feasible to efficiently multiplex a P2P system across multiple, virtual private overlays enabling each profile owner to have a profile overlay consisting of their online friends. For access control, we employ a PKI, where each member uses the signed certificate generated during the "finding and verifying friends" stage. All links are encrypted using symmetric security algorithms established through the PKI, thus preventing uninvited guests from gaining direct access to the overlay and hence the profile. Because the profile owner also is the CA for all members of the overlay, they can easily revoke users from access to the profile overlay. In [90], we described mechanisms for overlay revocation through the use of broadcasting for immediate revocation and the use of DHT for indirect and permanent revocation.

The message board of a profile can be stored in two ways: distributed within the profile overlay via a data store or stored on the profile owner's personal computing devices. The distributed data store provide the profile when the owner is offline and also distributes the load for popular profiles. For higher availability, each peer should always be a provider for all data in their profile when they are online. To ensure authenticity and integrity, all peers should sign their messages and each peer's certificate should be available in the overlay for verification. Messages that are unsigned should be ignored by all members of the overlay. An ideal overlay for this purpose should support complex queries [43] allowing easy access to data stored chronologically, by content, by type, i.e., media, status updates, or message board discussions.

Private messaging in the profile overlay is unidirectional meaning that only the profile owner can receive private messages using their overlay. To enforce this, a private message should be prepended with a symmetric key encrypted by the profile owners public key, the message should be appended by a hash of the message to ensure integrity and the entire message encrypted by the symmetric key. This approach ensures that only the sender and the profile owner can decrypt the private message. The contents of the private message should include the sender, time sent, and the subject. Messages can be stored in well known locations, so that the profile owner can either poll the location or, alternatively, use an event based system to notify them of the new message.

6.2.3 Active Peers

The directory overlay should be used to assist in finding currently active peers in the profile overlays. By placing their node IDs at a well-known, unique per-profile overlay keys in the DHT, active peers can bootstrap incoming peers into the profile overlay. We implemented and evaluated this concept in [90]. Because the profile overlay members all use PKI to ensure membership, even if malicious peers insert their ID into the active list, it would be useless as the peer would only form connections with peers who also have a signed certificate.

6.3 Challenges

While structured P2P overlays have been well-studied in a variety of applications, their use in social profile overlays raises new interesting questions, including:

1) Handling small overlay networks - P2P overlay research typically focuses on networks larger than the typical user's friend count (Facebook's average is 130[1]). Because social profile overlays are comparatively smaller, this can impact the reliability of the overlay and availability of profile data. A user can host their own profile; however

[1] http://www.facebook.com/press/info.php?statistics

when the user is disconnected it is important that their profile remains available even under churn. It is thus important to characterize churn in this application to understand how to best approach this problem. An optional of per-user deployment of a virtual individual server (VIS) and the use of replication schemes aware of a user's resources provide possible directions to address this issue.

2) Overlay support for low bandwidth, unconnected devices - devices such as smart phones cannot constantly be actively connected to the overlay and the connection time necessary to retrieve something like a phone number may be too much to make this approach useful. Similar to the previous challenge, this approach could benefit from using a VIS enabling users access to their social overlays by proxy without establishing a direct connection to the overlay network.

3) Reliability of the directory and profile overlay - Overlays are susceptible to attacks that can nullify their usefulness. While the profile overlay does have point-to-point security, in the public, directory overlay, the lack of any form centralization makes policing the system a complicated procedure. While our approach of appending friends list can assist users in making decisions on identity, it does not protect against denial of service attacks. For example, users could attempt create many similar identities in an attempt to overwhelm a user in their attempt to find a specific peer. Previous work has proposed methods to ensure the usability of overlays even while under attack. For the social overlay to be successful, we must identify which methods should be used. A possible approach is to replicate public information within a user's profile overlay thus providing an alternative directory overlay for querying prior to using the public directory overlay.

6.4 Figures and Tables

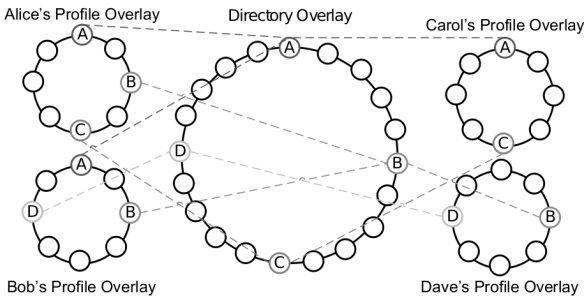


Figure 6-1. An example social overlay network. Alice has a friendship with Bob and Carol, hence both are members of her profile overlay. Bob has a friendship with Alice and Dave but not Carol; hence Alice and Dave are members of his profile overlay, while Carol is not. Each peer has many overlay memberships but a single root represented by dashed lines in various shades of gray. For clarity, overlay shortcut connections are not shown.

CHAPTER 7
CONCLUSIONS

In this proposal, I have explained the construction of scalable, decentralized VPNs. To support this work, I have designed and implement features to structured overlays improving their usability. Relays enable two-hop connections between peers that cannot form direct connections. Private virtual overlays provide a secure overlay and secure the VPN. Group environments make the creation of VPNs significantly easier. In addition, I designed and implemented a VPN architecture that supports both Interface and Router configurations combining the attractive features of each into a Hybrid approach.

APPENDIX: STRUCTURED OVERLAY BROADCAST

Brunet has an efficient broadcast model called bounded-broadcast because it is capable of broadcasting to a subset of nodes, though it is also capable of broadcasting to the entire overlay. A bounded broadcast uses the following recursive algorithm: Begin with node x triggering a broadcast message over the region $[x, y]$. x has F connections to nodes in the range $[x, y]$. Denoting the i^{th} such neighbor as b_i, the node x sends a bounded broadcast over a sub-range, $[b_i, b_{i+1})$, to b_i, except the final neighbor. Differently stated, b_i is in charge of bounded-broadcasting in the sub-range $[b_i, b_{i+1})$. If there is no connection to a node in the sub-range, the recursion has ended. The final neighbor, (b_F), is responsible for continuing the bounded broadcast from $[b_F, y]$. When a node receives a message to a range that contains its own address the message is delivered to that node and then routed to others in that range. Figure A-1 shows how this bounded broadcast forms a local tree recursively. The time required for a bounded broadcast is $O(\log^2 N)$ as shown in [52]. To perform a broadcast on the entire overlay, a peer performs the bounded-broadcast starting from its node ID with the end address being the node ID immediately preceding its own in the address space.

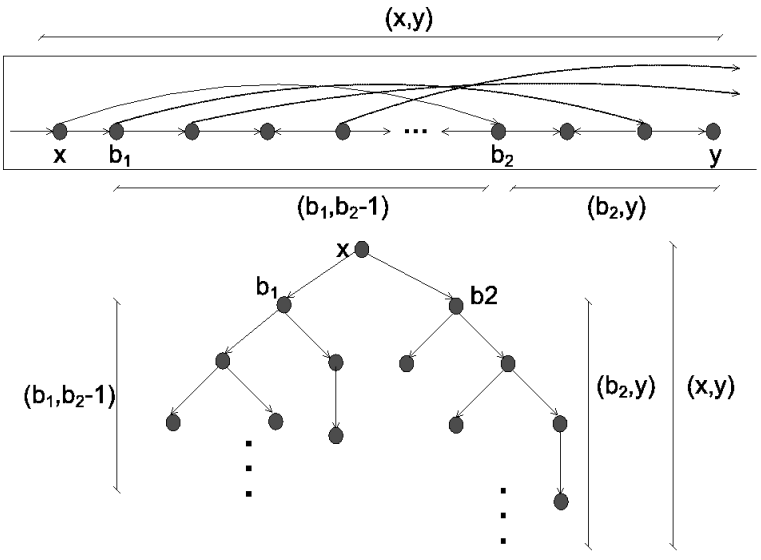


Figure A-1. Bounded Broadcast in range $[x, y]$

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BIOGRAPHICAL SKETCH

I am David Isaac Wolinsky born on October 31, 1982. I have been married to Donna Korin Wolinsky since June 2007 and was blessed with a son, Isaac Emmanuel, on November 30, 2009. I began my studies at the University of Florida's Electrical and Computer Engineering Department in August 2001, obtaining a bachelors of science degree in the spring of 2005 and masters of science degree in the spring of 2007 and now currently pursuing a doctorate of philosophy. My advisor is Professor Renato Figueiredo, whom I began working with since the spring of 2006 at the Advanced Computing and Information Systems Lab.

My primary research focuses are network virtualization using structured P2P overlays. This research work has been realized in IPOP, a free (GPL) network virtualization software. I have worked on enabling DHTs, decentralized NAT traversal through relays, software models for improved network virtualization, and autonomic virtual networking stacks. This work is a major contribution to my other research focus, Grid Appliance, which enables the creation of decentralized, distributed grids through virtualized, physical, and cloud resources.

During my free time, I enjoy time with my boy (son), running, playing basketball with the LBBA (Larsen-Benton Basketball Association) colleagues, and occassionally playing video games. At one point prior to engaging in the arts of seeking a Ph.D., I was ranked in the top 20 on the US East Warcraft III Free For All Ladder. Most of my time is split between the Archer project and attempting to finish my Ph.D. prior to turning 30, thankfully I have a few years prior to turning 30. During my deeper moments, I contemplate my struggle with the amazing gift that Christ as my savior gave to me in spite of my brokeness.