

Addressing the P2P Bootstrap Problem for Small Overlay Networks

Abstract—Peer-to-Peer (P2P) overlays provide a framework for building distributed applications consisting of few to many resources with features including self-configuration, scalability, and resilience to node failures. Such systems have been successfully adopted in large-scale Internet services for content delivery networks, file sharing, and data storage. The bootstrap problem, finding an existing peer in the overlay, remains a challenge to enabling these services for small-scale P2P systems. In large networks, the solution to the bootstrap problem has been the use of dedicated services, though creating and maintaining these systems requires expertise and resources, which constrain their usefulness and make them unappealing for small-scale systems. Decentralized, P2P systems can be useful in small-scale systems to address privacy concerns as well as support for network applications that lack dedicated, centralized bootstrap servers.

This paper surveys and summarizes requirements that allow peers potentially constrained by network connectivity to bootstrap small-scale overlays through the use of existing public overlays. In order to support bootstrapping a public overlay must support the following requirements: a method for reflection in order to obtaining a publicly reachable address, so peers behind network address translators and firewalls can handle incoming connection requests; rendezvous for discovering remote peers, when the overlay lacks stable membership; and communication relaying to share public addresses and communicate when direct communication is not feasible. After presenting a survey of various public overlays, we identify two overlays that match the requirements: XMPP overlays, such as Google Talk and Live Journal Talk, and Brunet, a structured overlay based upon Symphony. We present qualitative experiences with prototypes that demonstrate the ability to bootstrap small-scale private structured overlays from public Brunet or XMPP infrastructures.

I. INTRODUCTION

While P2P overlays provide a scalable, resilient, and self-configuring platform for distributed applications, their adoption rate for use across the Internet has been slow outside of large-scale systems, such as data distribution and communication. General use of decentralized, P2P applications targeting homes and small/medium businesses (SMBs) has been limited in large part due to difficulty in decentralized discovery of P2P systems — the bootstrap problem — further inhibited by constrained network conditions due to firewalls and NATs (network address translators). While these environments could benefit from P2P, many of these users lack the resources or expertise necessary to bootstrap private ¹ P2P overlays particularly when the membership is unsteady and across wide-area network environments where a significant amount of (or all) peers may be unable to initiate direct communication with each other due to firewalls and NATs.

Examples of large-scale P2P systems include Skype, BitTorrent, and Gnutella. Skype is a voice over P2P system, whereas BitTorrent and Gnutella are used for file sharing. The bootstrapping in these systems typically rely on overlay maintainers using high availability systems for bootstrapping, bundling their connection information with the application for distribution. When the application is started, it uses these high availability servers to connect with other peers in the system. Alternatively, some services constantly crawl the network and place peer lists on dedicated web sites. A new peer wishing to join the network queries the web site and then attempts to connect to the peers on that list.

In smaller-scale systems, P2P interests focus on decentralization. For example, users may desire to run an application at many distributed sites, but the application lacks dedicated central servers to provide discovery or rendezvous service for peers. In contrast, dedicated, centralized P2P service providers, such as LogMeIn's Hamachi, a P2P VPN, may collect usage data, which the users may wish to remain private, or are not free to use.

Many applications of small-scale P2P overlays can be envisioned, including multiplayer games, especially those that never or no longer have dedicated online services; private data sharing; and even distributed file systems. Clearly, a small P2P system could be bootstrapped by one or more users of the system running on public addresses, distributing addresses out-of-band, instructing their peers to connect to add that address to their P2P application, and then initiate bootstrapping; but these types of situations are an exception and not the norm. Ultimately, users require an approach that can make decentralized bootstrapping transparent through minimal and intuitive interaction with the P2P component.

The basic bootstrapping process can be broken down into two components: finding a remote peer, and then successively connecting to it and more peers. When a node begins, it contacts various bootstrap servers, until it successfully connects with one, upon which they exchange information. The bootstrap server may inquire into the overlay for the best set of peers for the new peer and respond with that information or it may respond with its existing neighbor set. At which point, the peer attempts to connect with those peers. This process continues aggressively until the peer arrives at a steady state, either connecting with a specific set of or a number of peers. Afterwards, the P2P logic becomes passive, only reacting to churn from new incoming peers or outgoing peers.

Overlay support for constrained peers, i.e., those behind NATs and restrictive firewalls, requires additional features to support all-to-all connectivity for peers in the overlay. The

¹In the context of this paper, private implies that the overlay's purpose is not for general use. Once established, such overlays can support privacy in communication; however, overlay security is beyond the scope of this paper.

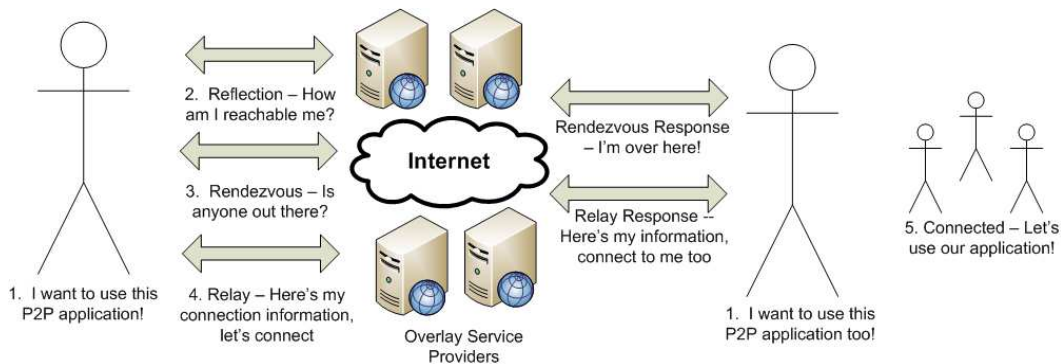


Fig. 1. Bootstrapping a P2P system using an existing (generic) overlay.

instantiation of P2P systems for private use could become overly burdensome, potentially relying on significant human interaction to bootstrap them, for example, by relaying connection information through phone calls and e-mail. Even if this is feasible, this sort of interaction is undesirable; P2P systems should be self-discovering so that users need to do minimal amount of work to take advantage of them and ad-hoc systems stress this point. In addition, these may rely on centralized components; if they become unavailable, which is a possibility since most users lack the expertise in configuring highly available systems, the system will not be accessible.

To address this, we explore the use of existing public overlays as a means to bootstrap small-scale private overlays. There are many existing public overlays with high availability, such as Skype, Gnutella, XMPP, and BitTorrent; by leveraging these systems, system integrators can easily enable users to seamlessly bootstrap their own private P2P systems. In the preceding paragraphs, we identified the components necessary for bootstrapping a homogeneous system; now we expand them for environments to support the bootstrapping of a private overlay from a public overlay with consideration for network constrained peers. The public overlay must support the following mechanisms as illustrated in Figure 1:

- 1) **Reflection** - Constrained peers must have some method of determining their Internet connection information, to share with other constrained peers to enable direct connectivity.
- 2) **Rendezvous** - Peers seeking members of a private overlay in a public overlay must be able to identify each other.
- 3) **Relaying** - Peers must be able to exchange arbitrary data to share connection information and to enable direct links across NATs when possible or, otherwise, as a relay.

This work motivates from the belief that what prevents use of small-scale P2P systems is due to lack the resources, technical knowledge, and lack of ability and desire to create and manage high availability bootstrap services. A public overlay can be used to transparently bootstrap a private overlay with minimal user interaction.

The requirements are presented and verified in the context of two prototype implementations: a XMPP (Jabber) [1] and Brunet [2]. XMPP or Extensible Messaging and Presence Protocol based overlays are commonly used as chat portals, such as GoogleTalk and Facebook Chat. XMPP also supports an overlay amongst servers forming through the XMPP Federation, which allows inter-domain communication amongst chat peers, so that users from various XMPP servers can communicate with each other. Brunet provides generic P2P abstractions as well as an implementation of the Symphony structured overlay. We present the architecture for these systems, the lessons learned in constructing and evaluating them, as well as provide quantitative analysis of peer connectivity to a private Brunet overlay.

The organization of this paper follows. Section II presents common P2P overlay technologies, motivating examples for this work, existing solutions to the bootstrapping problem, and NAT challenges in P2P systems. In Section III, we present a survey of overlays, applying the requirements for private overlay bootstrapping to them, and then show in detail how they can be applied to Brunet and XMPP. Our implementation is described in Section ?? In Section V, we then perform a timing evaluation of bootstrapping overlays using our prototype PlanetLab and discuss experiences in deploying the system. Finally, we conclude the paper with Section VI.

II. BACKGROUND

Large-scale P2P systems typically come in two flavors: unstructured and structured. Unstructured systems [3], [4] are generally constructed by peers attempting to maintain a certain amount of connections to other peers in the P2P system, whereas structured systems organize into well-defined topologies, such as trees, 1-D rings, or hypercubes. Though unstructured systems are typically simpler to bootstrap and maintain, they rely on global knowledge, flooding, or stochastic techniques to search for information in an overlay, creating potential scalability constraints. Alternatively, structured systems [5], [6], [7], [8], [9]. Structured overlays have guaranteed search time typically with a lower bound of $O(\log N)$ and in some cases even $O(1)$ [10].

Most structured overlays support a decentralized storage / retrieval system called a distributed hash table (DHT), that

maps keys with associated data 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 key, for fault tolerance the data can be stored at other nodes. DHTs can be used by peers of systems to coordinate allocation and discovery of resources, making them attractive for self-configuration in decentralized collaborative environments.

Another subset found of P2P systems are those that are not fully decentralized, such as "P2P VPNs" like Hamachi [11], older systems like the original Napster, and tracker-based BitTorrent. These types of systems provide a rendezvous services for peers to discover each other to form direct, or P2P, connections with each other for the purpose of network connectivity or data sharing. BitTorrent differentiates itself by using the trackers as a gateway into the overlay, once inside, peers exchange connection information with each other directly relegating the tracker as a fall back. This approach has enabled BitTorrent to be modified to support trackerless torrents through using a DHT.

A. Applications

In this section, we present applications and potential ways to configure them to use a private overlay. The work relies on a public key infrastructure and secure point-to-point and end-to-end communication for P2P as described in our technical report [12]. The applications we investigate 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 free-to-join public overlay.

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 [13], 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 [14], 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 could easily be used as servers for IRC, do not require global knowledge, and can be configured to handle connectivity issues.

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 consisting of their friends. The overlay should include a secured DHT, where only all writes are signed to uniquely identify the creator and may only be removed by the owner of the overlay. 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 then consist of the accumulation of the individual private overlays and the public overlay.

3) *P2P VPNs*: Private overlays enable truly decentralized, 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. SocialVPN [15] relies on a dedicated bootstrap overlay provided by University of Florida. Using the techniques described in this paper, SocialVPN could be extended so that it can be bootstrapped into private systems without additional user configuration.

4) *Multicast*: The topic of secure multicast has been a focus of much research. Using an approach similar to CAN [16], 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 as described in [17]. Examples of such services include light weight multicast DNS / DNS-SD (service discovery), as well as audio and video streaming.

B. Bootstrapping P2P Systems

As described in the introduction, the simple case of bootstrapping is limited to one peer attempting to find an active peer in the overlay in order for itself to become a member. The large-scale providers have resources not readily available to small-scale overlays. This section presents the existing techniques and those being developed and describes their application to small-scale systems.

When using dedicated bootstraps, a service provider hosts one or more bootstrap resources. Peers desiring to join the overlay query bootstrap nodes, until a successful connection is made to one. The bootstrap server will then assist in connecting the peer to other nodes in the P2P system. Bootstrap nodes are either packaged with the application at distribution time or through a meta data file, such as in BitTorrent. Drawbacks to this approach for small, ad hoc pools include that the same server would have to be used every time to bootstrap the system, or users would have to reconfigure their software to connect to new bootstrap servers over time; at least one peer to have a publicly accessible address; and it can become a single point of failure.

Another commonly used approach for large-scale systems is the use of a host cache [18]. Clients post current connection information to dedicated web services, a host cache, that in turn communicate with other host caches. For small, ad hoc networks, a host cache acts no differently than a centralized rendezvous point, requiring that at least one peer has a publicly accessible address.

“P2P VPN’s” [19] use of a BitTorrent tracker is similar to the host cache concept. The tracker hosts file meta data and peers involved in sharing. For the VPN, the peer registers a virtual file that is used to organize the peers, a form of rendezvous. When a peer accesses a tracker, it registers its IP and receives other active “sharers” IP addresses. Peers on public addresses or using UPNP are able to receive incoming connections from all other peers. The problem with this approach is that it is heavily user driven. A user must register with each BitTorrent tracker individually and maintain a connection with each of them, in order to handle cases where BitTorrent trackers go offline. In addition, this does not use the BitTorrent trackers in a normal fashion, so it may be banned by tracker hosts.

Research has shown that peers can use the locality properties of recent IP addresses in a large-scale P2P system to make intelligent guesses about other peers in the P2P system using an approach called random probing [20], [21]. The results show for networks in the order of tens of thousands that a peer can find an active peer node within as few as 100 attempts and as many as 2,000 guesses. The application of this approach to small, ad hoc groups is challenging. Peers behind NATs would most likely be unable to receive probe attempts, further more, if peers are widely distributed and the system small, this approach may have to query the majority of the IP address range to find a peer. The results were not tested in real systems, but instead using overlay traces.

Rather than distribute an IP address, which points explicitly to some location in the Internet, a small P2P network can apply a name abstraction around one peer in the overlay using Dynamic DNS [22]. In this approach, peers share a common DNS entry, providing an abstracted mechanism for labeling the bootstrap peer. When the peers detect that the IP directed to by the DNS entry is offline, they replace it with their own. The application of this approach to small, ad hoc groups is actually quite nice, as the service could be distributed across multiple Dynamic DNS registrations. The significant drawback to the approach is that the dynamic DNS server could be attacked, since the login information must be shared amongst all peers in the overlay. Also the approach requires that at least one peer be publicly addressable and know that it is, if a non-publicly addressable peer updates the cache, it could delay or permanently prevent peers from creating a P2P system. The results were simulation based and did not determine how well a dynamic DNS handles rapid changing of name to IP mappings.

IP supports multicasting to groups interested in a common service. In the case of bootstrapping a P2P system [5], [21], all peers would be members of a specific group. When a

new peer comes online, it queries the group for connection information and connects to those that respond. The approach, by itself, requires that all peers are located in a multicast capable network, typically spanning only local area networks.

A large-scale structured overlay [23], [24] could enable peers to publish their information into a dedicated location for their service or application and then query that list to obtain a list of online peers. Peers could search for other peers in their overlay and connect with them using their connection information. Since the service would be a large-scale system, it could easily be bootstrapped by a dedicated bootstrap or host caches. As it stands, the described works were position papers and the systems have not been fully fleshed out. The primary challenge in relationship to small, ad hoc networks is that it lacks details bootstrapping of peers behind NATs into overlays as it provides only a means for rendezvous and no reflection nor relaying.

C. NAT Hampering the Bootstrap Process

As of 2010, the majority of the Internet is connected via Internet Protocol (IP) version 4. This protocol has a quickly approached limit of addresses available, only 2^{32} (approximately 4 billion). With the Earth’s population at over 8 billion and each individual potentially having multiple devices with Internet connectivity, the IPv4 limitation is becoming more and more apparent. Addressing this issue are two approaches: 1) the use of NATs to enable many machines and devices to share a single IP address but preventing bidirectional connection initiation, and 2) IPv6 which supports 2^{128} addresses. The use of NATs complicates the bootstrapping of P2P systems as it prevents peers from simply exchanging addresses with each other to form connections, as the addresses may not be public. In addition, firewalls may prevent peers from receiving incoming connections. Thus while the eventual widespread use IPv6 will cause the demise of NATs, though this is not guaranteed, it does not deal with the issue of firewalls preventing P2P applications from communicating.

When a machine, A , behind a typical NAT, B , sends out a packet to an Internet host, C , the NAT device translates the packet so that it appears it is coming from the NAT device. The packet sent from A to C has the source and destination $IP : port$ pairs expressed as $IP_A : Port_A$ 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 [25], [26]. 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 it 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 it 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.

Because of the nature of NATs two peers behind them attempting to communicate with each other will not be able to seamlessly exchange correct addressing information for each other. Section III-A describes techniques that enable peers to exchange routable addresses with each other and Section III-B describes relaying solutions, the alternative when two peers are unable to communicate directly.

III. CORE REQUIREMENTS

As presented in the preceding sections, a solution to bootstrapping small P2P overlays must address several challenges, namely reflection, rendezvous, and relaying. In this section, we present a generic solution to this problem. At the basis of our solution is the use of a publicly available free-to-join public overlay. In order to support these features the public overlay must have mechanisms for peers to obtain a public network identity, reflection; search for other peers that are bootstrapping the same P2P service, rendezvous; and send messages to peers through the overlay, relaying. These are the minimum requirements to bootstrap a decentralized, P2P system when all peers are behind NATs.

A. Reflection

Without a reflection, two peers on different networks with non-public addresses would not have routable addresses with which to communicate with each other. For constrained resources, the two solutions for traversal are hole punching and relaying. In hole punching two peers attempt to form a direct connection by tricking the NATs to believe that the internal peer has already established communication with the external peer. This works, because both peers do it simultaneously.

In IP communication, the simplest method for NAT traversal is the multiplexing of a single UDP socket, IP address and port combination. This behavior can be supported through either local configuration or remote assistance. The local configuration approach relies on the local router supporting either UPNP [27] or port forwarding / tracking. In many cases, UPNP is not enabled by default and in most commercial venues it will rarely be enabled. Port forwarding / tracking require a more detailed configuration of a router, outside the comfort range of many individuals and is not uniform across routers. A peer using UPNP needs no further services, as UPNP enables a peer to set and obtain both public IP address and port mappings. Port forwarding and tracking mechanisms still require that the user obtains and inputs into the application their public IP address or use in band assistance described next.

In the remotely assisted scenario, a peer first sends a message to a reflection provider, perhaps using STUN [28]. The response from the provider tells the peer from which IP address and port the message was sent. In the case of all cone NATs, this will create a binding so that the peer can then share that IP address and port with other peers behind NATs. When the two peers communicate simultaneously all types of cone NATs can be traversed. So long as one peer is behind a cone NAT, NAT traversal using this mechanism is possible. The situation becomes complicated when both peers are behind symmetric NATs or when either one of them have a firewall prevent UDP communication. While there exist methods to traversing both symmetric and TCP only NATs, they are significantly more complicated than the reflection approach provided by STUN.

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 the various cone NAT types. [29] describes methods to traverse these NATs so long as there is a predictable pattern to port selection.

Unlike UDP, TCP NAT traversal is complicated by the state associated with TCP. In many systems, the socket API can be used to enable a peer to both listen for incoming connections and form outgoing connections using the same local addressing information. This is allowed in the TCP specification, but this is a non-traditional method of employing the sockets API. According to [30], this method works for various types of systems though the success rate on NATs is quite low, 40%. Other mechanisms rely on out of band communication, [31], or use of complicated predictive models [32].

These NAT traversal services only deal with a small portion of the bootstrap problem, reflection. That is, peers are able to obtain a public address for receiving incoming connections. They provide no means for users to exchange addresses with each other or perform simultaneous open. To address this issue many systems incorporate these NAT traversal libraries and use intermediaries to exchange addresses.

An example application that uses reflection, rendezvous, and relay services is is Teredo [33]. Teredo offers globally identifiable IPv6 addresses to everyone. The IPv6 address is constructed in a way to maps to a specific Teredo gateway, client pair. When two peers using Teredo attempt to connect with each other after exchanging their IPv6 addresses out of band, the Teredo servers exchange the clients IPv4 information obtained using a STUN-like procedure. The approach is heavily centralized and if the gateway peer goes offline or becomes saturated, the peers outgoing and incoming requests may be ignored.

B. Relaying

In an overlay, there exist two forms of relaying: one to exchange connection information and to assist in simultaneous connections and the other would be similar to the TURN style, arbitrary data router. Without a relaying mechanism

peers behind some of the various types of cone NATs would be unable to establish direct connections between each other. In the other case, there exists no silver bullet, guaranteed method, for dealing with NAT hole punching. Relays are the only guaranteed solution for NAT traversal, though it does not come cheaply. Relaying requires an entity willing to provide the service and traffic that can handle the potential delay and bandwidth limitations. In general, TURN is not very scalable as it requires a dedicated service provider. The designers of Teredo found relaying unattractive enough that it was not included in the Teredo package and thus peers behind severely constrained NATs are unable to communicate with each other.

A decentralized mechanism for relaying is ideal. In this case, a peer has an identifier that is loosely coupled with their network identity and even less to the overlay provider. When a remote peers sends a message to the identifier, the overlay should translate the identifier into network level addresses and forward it to the destination. This layer of decoupling could enable a scalable approach to relaying.

Relaying must, also, be a somewhat reliable enabling peers to exchange various sized, arbitrary messages. In this case, somewhat reliable means that the service provides at a minimum behavior like UDP, which has been described as an unreliable protocol. When a peer sends a message, it should expect the remote peer should receive it in a reasonable amount of time or not at all. If the sending peer does not receive a response within a reasonable amount of time, follow up requests can be sent until successful or it is deemed the remote party is no longer online.

Finally, the service should be asynchronous or event driven. The previous requirements would allow peers to relay through a message board or even by posting messages to a DHT. The problem with these two approaches is that peers may very well communicate for long periods of time using these services. That means the potential for posting large amounts of data to a service that will retain it and constantly querying the service to determine if an update is available. Both of these are highly undesirable and may be viewed as denial of service or spam attacks.

C. Rendezvous

Rendezvous enables peers to have a method for having a predetermined mechanism to discover each other. In the simplest case, a peer could randomly probe other peers on the Internet until it finds a matching peer. This approach is unreasonable if overlay is small and even more so if the peers are behind NATs, as the NATs may very well ignore the requests even if a peer behind the NAT is actively looking for that overlay as well.

Given an overlay, the most straightforward mechanism for rendezvousing is the use of a broadcast query to determine if any other peers are using the same service. In small enough overlays, this is a perfectly reasonable approach. Though in large scale systems such as Gnutella, the approach would never work.

There is not one unified method to consolidate rendezvous as doing such would severely limit its capabilities. Programming rendezvous using the unique features of an overlay can enable more efficient forms of rendezvous enabling peers to increase the likelihood of finding a mutual peer and doing so more quickly. For example, in the case of a DHT, peers can use a single DHT key to store multiple values, all of which would be addresses used to communicate with peers in the overlay. Alternatively, in a system like BitTorrent, peers could use the same tracker and become “seeds” to the same virtual file.

D. Overlay

A single public overlay does not need to provide all the components for bootstrapping the private overlay. For example, peers could use the the Limewire / Gnutella Kademlia DHT, Mojito, as a means to register for rendezvous. The peer could leave their globally unique XMPP identity in the DHT. Another peer interested in the same service would discover this identity and then could become friends through XMPP, an automatable process. Once the friendship has been formed, they can use XMPP as a means for relaying.

Additionally, a single reflection does not need to be limited to obtain routable IP addresses. For example, when a peer communicates through a relay provided by a service, it needs a global address for peers to direct messages towards it. A reflection service in this regards could be the overlays provision of a resource identifier.

IV. IMPLEMENTATIONS

Table I reviews various overlays, the majority of which are high availability, public, free-to-join overlays, though some research only overlays are included. From this list, we chose to extend Brunet and XMPP to support private overlay bootstrapping. Brunet provides a structured P2P infrastructure, though lacks an active, large-scale deployment outside of academic institutions due to being rooted in an academic project. XMPP, on the other hand, enables connections between friends with routing occurring across a distributed overlay.

Our implementation makes heavy use of the transports incorporated into Brunet [2]. The key distinguishing feature of this library is the abstraction of sending over a communication link as it supports primitives similar to “send” and “receive”. In the next sections, we will describe how we extended Brunet to be self-bootstrapping as well as extensions to enable bootstrapping from XMPP.

Our application of structured overlays as the basis private overlays is unique in that most publications regarding structured overlays focus on their ability to scale their ability to scale applications have employed them in the order of 10s to 100s of nodes. For example, Amazon’s shopping cart runs on Dynamo [37] using a “couple of hundred of nodes” or less. Facebook provides an inbox search system using Cassandra [38] running on “600+ cores”. Structured overlays simplify organization of an overlay and provide each member a unique identifier abstracted from the underlying network.

	Description	Reflection	Rendezvous	Relay
BitTorrent	Default BitTorrent implementations rely on a centralized tracker to provide the initial bootstrapping. Peers can establish new connections through information obtained from established connections. This relegates the tracker as a means of monitoring the state of the file distribution. BitTorrent specifies a protocol, though each client may support additional features not covered by the protocol.	The current specification does not support NAT traversal, though future versions may potentially use UDP NAT traversal. At which point, BitTorrent may support a reflection service.	Peers can register as seeds to the same file hash, thus their IP address will be stored with the tracker.	Peers receive each other's IP addresses from the tracker, there is no inherent relaying.
Gnutella	Gnutella is a large-scale unstructured overlay, consisting of over a million and, primarily, is used for file sharing. Gnutella consists of a couple hundred thousand ultra (super) peers to provide reliability to the overlay. Gnutella is free-to-join and requires no registration to use.	Work in progress. Peers attempt to connect to a sharers resource, though a "Push" notification reverses this behavior. Thus a peer behind a NAT can share with a peer on a public address.	Peers can perform broadcast searches with TTL up to 2, when networks consist of millions of peers, small overlays will most likely not be able to discover each other.	Not explicitly, could potentially utilize ping messages to exchange messages.
Skype	Skype is a large-scale unstructured overlay, consisting of over a million active peers, and primarily used for voice over P2P communication. Skype, like Gnutella, also has super peers, though the owners of Skype provide authentication and bootstrap servers. Though Skype is free-to-join, it requires registration to use.	Skype APIs provide no means for reflection.	Skype supports applications, or add-ons, which can be used to transparently broadcast queries to a users friend to determine if the peer has the application installed. Thus Skype does support rendezvous.	Skype applications are allowed to route messages via the Skype overlay, but because Skype lacks reflection, all communication must traverse the Skype overlay.
XMPP	XMPP consists of a federation of distributed servers. Peers must register an account with server, though registration can be done through XMPP APIs without user interaction. XMPP is not a traditional P2P system, though it has some P2P features. XMPP servers on distinct servers are able to communicate with each other. Links between servers are created based upon client demand. During link creation, servers exchange XMPP Federation signed certificates.	While not provided by all XMPP servers, there exist extensions for NAT traversal. GoogleTalk, for example, provides both STUN and TURN servers.	Similar to Skype, XMPP friends can broadcast queries to each other to find other peers using the same P2P service. Thus XMPP supports rendezvous.	The XMPP specification allows peers to exchange arbitrary out of band communication with each other. Most servers support this behavior, even when sent across the Federation. Thus XMPP supports relaying.
Kademlia [8]	There exists two popular Kademlia systems, one used by many BitTorrent systems, Kad, and the other used by Gnutella, called Mojito. Kademlia implements an iterative structured overlay, where peers query each other directly when searching the overlay. Thus all resources of a Kademlia overlay must be publicly addressable.	Existing implementations of Kademlia does not support mechanisms for peers to determine their network identity.	Peers can use the DHT as a rendezvous service, storing their connectivity information in the DHT at key location: <i>hash(SERVICE)</i> .	An iterative structured overlay has no support for relaying messages.
OpenDHT [34]	OpenDHT is a recently decommissioned DHT running on PlanetLab. OpenDHT is built using Bamboo, a Pastry-like protocol [5]. Pastry implements recursive routing, peers route messages through the overlay.	Existing implementations of Bamboo and Pastry do not support mechanisms for peers to determine their network identity. Though this is ongoing work.	Peers can use the DHT as a rendezvous service, storing their connectivity information in the DHT at key location: <i>hash(SERVICE)</i> .	Because Pastry uses recursive routing, it can be used as a relay. Furthermore, extensions to Pastry have enabled explicit relays called virtual connections [35].
Brunet [2]	Brunet like OpenDHT is a freely available DHT running on PlanetLab, though still in active development. Brunet creates a Symphony [7] overlay using recursive routing.	Brunet supports inherent reflection services, when a peer forms a connection with a remote peer, the peers exchange their view of each other.	Peers can use the DHT as a rendezvous service, storing their connectivity information in the DHT at key location: <i>hash(SERVICE)</i> .	Like Pastry, Brunet supports recursive routing and even supports relays called tunnels [36].

TABLE I

Further more, as mentioned in the cited works, they provide high availability and autonomic features that can handle churn well. Further more, when used in small networks, most structured overlays act as $O(1)$ systems, explicitly all-to-all though in some cases with relaying, this includes Brunet and Pastry. Brunet explicitly supports all-to-all though in some cases may require constrained peers to route through relays. This can further be ensured by setting the amount of near connections for the infrastructures, which in Brunet is configurable at run time.

The XMPP library we used is called Jabber-Net. Each connection between peers is uniquely identified by employing socket like concepts, i.e., a pair of addresses and ports. The basic representation for this constitutes a pair of identifiers of the form "brunet://P2P_ID:PORT", where each peer has a unique ID and port associated for the local and remote entity. The XMPP implementation has a similar format: "xmpp://USERNAME@DOMAIN:PORT/RESOURCE", again one identifier for the local peer and one for the remote.

A. Bootstrapping Private Overlays Using Brunet

Prior to our work, Brunet bootstrapped using a recently online cache of peers and IP multicast. We have implemented Brunet to support STUN, such that, with every connection Brunet makes, peers inform each other of their view of the remote peers network state, a form of passive **reflection**. Furthermore, peers route through the overlay their intentions to connect with each other through “ConnectToMe” messages. Thus when a peer desires a connection to another, both peers simultaneously attempt to connect to each other, dealing with the issue of more restrictive cone NATs and the case when the peer is behind a non-traversable NAT. To address the situation where two peers are behind symmetric NATs or one does not allow UDP, Brunet has been enhanced to support “Tunnels” [36], where peers route to each other through their other connections.

In Brunet, we chose to use the DHT for **rendezvous**, as this provides a scalable and self-maintaining mechanism for maintaining a bootstrap. All peers interested in a specific service or private overlay obtain a DHT key based upon a hashing of the service or private overlay’s name. Peers can then query this entry in the DHT to obtain a list of peers in the private overlay. Note, that Brunet’s DHT implementation supports a single key may have many values. Since DHTs are soft state, or lease systems, where data is released after a certain period of time. Peers must actively maintain their DHT entry. The DHT is a lease or soft state system, where (key, value) pairs are inserted into it with a time to live, after which, the key is removed from the DHT. Thus a peer who is online can actively maintain their DHT entry and when the peer goes offline, it need not explicitly remove the entry.

For **relaying**, we further extended Brunet’s transport library to support treating an existing overlay as a medium for point-to-point communication, we call this a “Subring” transport. Thus in the DHT, peers store their public overlay address. When the private overlay transmits data across the public overlay, it sets the protocol type to match a unique value for the specific overlay and then sends the packet through the greedy routing mechanisms on the public overlay to the remote peers public overlay address. In order to instruct peers to establish “Subring” links, they exchange an identifier that instructs them to do so of the form “brunet://P2P_ID:PORT”.

The final challenge faced was the application of Brunet’s reflection service for the private overlay. There were two directions we could have gone. The first would have been to extend Brunet to support STUN in each of the remote servers and then have a private node query them for their public information. The problem with this approach is that it would require maintaining additional state, such as figuring out which of the remote peers are on public addresses and can provide STUN services.

Instead, we opted to multiplex the socket used for the public overlay as it already had gone through the process of “reflection”. We call the multiplexing of a single socket for multiple overlay “Pathing”. In this context, the public and private overlays are given a virtual transport layer

that hooks into an underlying transport layer, thus not limited purely to socket transport layers. When peers exchange identifiers, instead of transmitting a simple identifier like “udp://192.168.1.1:15222”, the “Pathing” library extends it to “udp://192.168.1.1:15222/path”, where each path will signify a unique overlay.

B. Bootstrapping Private Overlays Using XMPP

The key features that make XMPP attractive are the distributed nature of the federation and the openness of the protocol. As of December 2009, there are over 70 active XMPP servers in the XMPP Federation [39]. These include GoogleTalk, Jabber.org, and Live Journal Talk.

In XMPP, each user has a unique identifier of the form “username@domain”. Where the domain specifies the client XMPP server and the username explicitly identifies a single individual. XMPP supports concurrent instances for each user by appending a resource identifier to the user ID: “username@domain/resource”. A resource identifier can either be provided by the client or generated by the server. For users in the same domain, the server forwards the message from source to destination. When two users are in different domains, the sender’s server forwards the message to the receiver’s server, who then relays it to the receiver. Peers are able to send text messages to each other as well as arbitrary binary messages called “IQ”.

Peer relationships are maintained by the server. Peer initiate them through an in band subscription mechanism based upon “IQ”, allowing clients to handle the process of adding and removing peers. Once peers have established a connection or subscription, they are informed through a “Presence” notification that the peer has come online, this include the full user identifier.

The **reflection** component in XMPP is available only to those servers that support a feature called “Jingle” [40]. “Jingle” uses “IQ” to determine available STUN and TURN servers. Fortunately, these services are provided free of charge through GoogleTalk. In Brunet, we extended the UDP transport to support querying STUN servers so that it can obtain an address mapping and keep it open. STUNs protocol sets the first two bits to 0 in all messages, thus we used that and the STUN cookie to distinguish it from other messages.

Rendezvous can be approached in two methods. We could simply broadcast a discovery “IQ” to all our peers looking for a remote service, though this may be viewed by the server as some sort of attack. Alternatively, a resource identifier could be used to set apart P2P peers from chat peers. The problem with this approach is what if two P2P applications use the same base identifier. Our solution combines the two approaches, so that during the Presence notification, a peer learns about potential P2P peers. Then when the peer is actively querying for remote addresses, it will also inform the queried peer about the type of P2P service requested. If the peer’s having matching P2P services, the peer will return a list of addresses otherwise it returns an empty list.

In order to support the situation, where two peers are unable to communicate through the exchanged addresses, we have extended XMPP “IQ” as a transport to support **relaying**. In the exchanged addresses from the rendezvous phase, one of the addresses is of the form “xmpp://username@domain/resource”. Once a peer has formed a connection through XMPP, they are then able to attempt simultaneous connection attempts, further increasing the likelihood of a connection. If that does not succeed, the peers can still relay through XMPP. This approach also has the benefit that, if a XMPP server does not support “Jingle”, the two peers can still form links with each other. Since Brunet supports reflection, eventually, if one of the peers in the system has a public address, it will automatically assist the other peers into forming direct links with each other.

V. EVALUATING OVERLAY BOOTSTRAPPING

In this section, we present a qualitative evaluation of our prototype bootstrapping a small-scale network and also share some experiences with deploying overlays.

A. Deployment Experiments

The purpose of our experiment is to verify that our techniques work and what overheads should be expected in using Brunet and XMPP to bootstrap an overlay. The experiments in no means are rigorous as that would become overly focused on overheads of Brunet and XMPP, instead this paper is primarily interested in forming small-scale overlays. The experiment represents 5 peers desiring all-to-all direct connectivity a feature transparently available to them if they bootstrap into a private Brunet overlay.

This experiment relied on a public Brunet overlay consisting of over 600 nodes running on PlanetLab. PlanetLab [41] 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 us 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.

GoogleTalk provided the XMPP overlay used in this experiment. Though this experiment does not take into advantage the features of the XMPP Federation, this aspect is presented in more detail in the next section reviewing experiences deploying overlays using XMPP.

B. Deployment Experiences

In this section, we share some our experiences in deploying XMPP overlays. Recently, Facebook announced that they would be supporting XMPP as a means to connect into Facebook chat. This was rather exciting and further motivated this work, as Facebook has over 400 million active users, which would have made there XMPP overlay, potentially, the largest free-to-join overlay. Unfortunately, experiments established that Facebook does not actually employ a traditional XMPP setup. The Facebook XMPP setup merely provides a proxy

into their chat network, preventing features like arbitrary IQs and other forms of out-of-band messages to be exchanged between peers. That alone was not the nail in the coffin, as messages could have still been exchanged encoding the binary data as text messages between peers. The nail in the coffin was that translation performed on peers identifiers. For example, a user would generate a XMPP identifier of the form “username@chat.facebook.com/resource”, but to its peers, it would be presented as “uSOME_NUMBER@chat.facebook.com”. Thus peers would then need to use another service just to obtain the identity of the peer and would have no means to tell what the resource identifier is. The only approach to bootstrapping would be to broadcast in-band messages to all peers, the problem with this is that many peers may actually be using the chat system for chatting. These peers would receive spam from an overlay bootstrap, which they may not be very receptive to. Finally, Facebook is not a part of the XMPP Federation, thus peers from GoogleTalk cannot chat with peers from Facebook. Given that there was no way to exchange arbitrary information and the rendezvous service was crippled, at this point in time, it appears there is no way to bootstrap an overlay using Facebook.

During initial tests in verifying the workings of the XMPP code base, we bootstrapped a private Brunet overlay on PlanetLab through various XMPP service providers. Interestingly, GoogleTalk servers seem to ignore machines on PlanetLab. Using another provider, the service appeared to crash after 257 instances of the same account were online. Unfortunately, the provider had no contact information available, so we were unable to determine if our test caused the crash. There was one server that appeared have no trouble hosting 600 concurrent instances of a single XMPP user, “jabber.rootbash.com”. The nodes were able to rendezvous and relay through *rootbash* and form a connected P2P system. The setup did not require reflection, as PlanetLab resources all have public IP addresses.

Once the system was running on PlanetLab, more tests were performed to determine the ability to bootstrap across the XMPP Federation. We formed friendships, or subscriptions, between users across a few different XMPP service providers. In the most evaluated case, a single peer on GoogleTalk and the PlanetLab system using *rootbash*, the GoogleTalk peer would not always receive presence notifications for all peers online, though always would receive some. When a peer began the relaying mechanism, it would broadcast to every peer, it rendezvoused or discovered. When performing this between GoogleTalk and *rootbash*, the GoogleTalk peer would not receive a response. Though in reducing the broadcast to a random selection of 10 peers, every 10 seconds until the GoogleTalk peer was connected, the peer received responses. The behavior indicates that the XMPP servers may have been filtering to prevent denial of service attacks. One last note, when bootstrapping a peer from GoogleTalk into the *rootbash* system, it always took 1 minute for the node to become fully connected to the private overlay. When the peer used *rootbash*, the peer always connected within 30 seconds. It seems as if the communication between XMPP servers was being delayed for

some reason. The same behavior was not experienced, when chatting between the two peers.

VI. CONCLUSION

In this paper, we have established the requirements for bootstrapping small-scale P2P overlays, reflection, rendezvous, and relaying. Reflection is required, so that peers behind NATs and firewalls can obtain a public address to share with remote peers. Rendezvous is a common problem, even for large-scale systems, peers must have a mechanism to find other peers connecting to are in the same overlay. Finally, without relaying, peers behind NATs would be unable to exchange with each other their public addresses and perform NAT hole punching.

As we surveyed existing overlays, we found two systems that can easily satisfy the requirements, XMPP and Brunet. While Brunet can efficiently provide P2P services, it is an academic setup, XMPP, on the other hand, is production ready and distributed across many different providers, each offering interoperability. The only issue with using XMPP alone is that peers must already be friends in order to rendezvous. For future work, we will investigate how peers can leverage existing DHT deployments, such as Kad or Mojito, for rendezvous, form friendships automatically in XMPP, and continue the bootstrap process using XMPP. Our implementation successfully deals with the bootstrapping problem for small-scale overlays using decentralized technique.

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