2005

TCP Connections for P2P Apps: A Software Approach to Solving the NAT Problem

Jeffrey L. Eppinger
Carnegie Mellon University

TCP Connections for P2P Apps:
A Software Approach to Solving the NAT Problem

Jeffrey L. Eppinger
January 2005
CMU-ISRI-05-104

Institute for Software Research International
School of Computer Science
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

Abstract

Many P2P applications need to connect to each other via TCP, but are increasingly stymied by NAT boxes. Some popular P2P applications do not address NAT traversal or do so poorly. A few newer ones route communications between NATed peers through relay servers or through non-NATed peers, or they ask users to reconfigure their NAT boxes. Some emerging solutions suggest using SIP to set up tunneling over UDP, using UPnP, or even deploying IPv6. This paper argues that the above approaches suffer from scalability problems, do not address mobility issues, require deploying new network infrastructure, or require using non-standard communications interfaces, non-standard communication stacks, and non-standard security protocols. We advocate direct TCP connections between peers. We present NatTrav, our NAT Traversal Java package that makes TCP connections between NATed peers and addresses all of the above concerns. We then compare NatTrav with some of the other current and emerging solutions.

Keywords: P2P, peer-to-peer, NAT Traversal, TCP, network address translation.

1. The Problem

We are building some really cool peer-to-peer (P2P) applications. If you're reading this paper, we'll bet you are, too. Among the first problems we encountered was how to connect our P2P applications together. We want TCP connections between instances of our application running on mobile (or even desktop) machines that (i) connect to the Internet from various places so they don't have a fixed network address, and (ii) often connect to the Internet via a Network Address Translation (NAT) box. We must solve problem (ii) in light of problem (i). Here's a scenario: our applications run on notebook computers and PDAs that are sporadically connected to the Internet from a home network, the office, "free high-speed Internet" in a hotel room, or WiFi in a coffee shop. In most if not all of these scenarios, our application requires TCP connections between two machines that are both behind NAT boxes. *The problem is that computers attached to the Internet via NAT boxes can make outbound connections to non-NATed computers, but typically cannot receive inbound connections.*

NAT boxes allow several computers to share one public IP address [1]. The computers get private IP addresses and must send their communication to the public Internet through the NAT box. The NAT box uses port translation in order to determine which computer should receive the responses [2]. For example, when the NAT box receives communication from a private IP address and port, say `A:X`, it sends the communication out via its public IP address on a proxy port, say `NA:Y`. The NAT maintains a table of mappings. When responses come back to the NAT on `NA:Y` it forwards them back to `A:X`. Also, when `A:X` sends additional communication the NAT can (depending on the destination and the NAT's implementation) use the same proxy port `Y`.

Using the classifications in [3], there are four different ways NAT boxes implement the mapping between `A:X` and its proxy port `NA:Y` which we summarize below. Assume we initiate communication from `A:X` to a non-NATed computer at IP address and port `B:J` via `NA:Y`:

1) With a **Full Cone** mapping, `NA:Y` will handle communications between `A:X` and any other computer. Specifically, a computer `C`, knowing or guessing `NA:Y` would be able to communicate with `A:X`.

2) With a **Restricted Cone** mapping, communication sent from a computer `C` to `NA:Y` would only be forwarded to `A:X` if `A` had previously sent communication from port `X` to computer `C`.

3) With a **Port Restricted Cone** mapping, communication sent from a computer `C` using port `M` to `NA:Y` would only forward to `A:X` if `A` had previously sent communication from port `X` to `C:M`.

4) With a **Symmetric** mapping, the NAT allocates a different proxy port for each IP address and port with which `A:X` communicates. For example, if `A:X` subsequently communicates with `B:Q`, another NAT proxy port would be used, such as `Z`.

In the first three cases, which we call cone-type mappings, the NAT uses `NA:Y` for all future communications from `A:X` until the mapping is removed from the its internal tables. Mappings are only removed after a period of inactivity on `NA:Y`.

2. Current Approaches

Popular P2P applications have addressed the NAT Traversal Problem in different ways. Below we enumerate our concerns about how these applications address NAT Traversal:

1) If only one peer is NATed, have the NATed peer set up the connections (e.g., Kazaa [4], LimeWire [5]). This is only a partial solution: in a majority of the scenarios in which our applications run both peers will be NATed.

2) Recommend users configure their NAT boxes to forward incoming requests on specific ports to one computer behind the NAT (e.g., BitTorrent [6]). This is unacceptable because (a) several computers behind the NAT may need to run this application and (b) users may not have the technical capability or administrative access to configure the NAT.

3) Route P2P communication through central relay servers (e.g., Groove [7]). This approach is too expensive. As our application scales, we cannot afford to provide the CPU and network bandwidth.

4) Route TCP connections through instances of the application that happen to be running on open, non-NATed computers (e.g., Skype [8]). We believe users who happen to be running our applications on non-NATed machines will not want to bare the CPU and network costs either. Moreover most machines running our applications will be NATed so there may be shortage of non-NATed machines to help out.

5) Use a proprietary session initiation protocol to exchange UDP ports between the peers and then tun-

nel TCP over UDP (e.g., Newrong [9]). We want to use a standard TCP stack with standard TCP stacks and interfaces so that we can capitalize on the benefits of the years of work optimizing TCP and building application packages for it. Also many networks do not allow UDP.

Finally, we have a security concern: our application requires the peers authenticate each other. We want to use SSL. Approaches 3, 4, & 5 require some sort of custom-made authentication scheme.

In Section 7, we discuss emerging solutions including UPnP, IPv6, and SIP.

3. Solution Requirements

Summarizing our concerns described above, our NAT Traversal solution should permit applications to talk to each other with:

a) **Scalability –** We want to incur minimal (if not zero) cost as the number of instances of our applications grows.

b) **Standard Interfaces –** For ease of development, we want to use standard interfaces for network communication, e.g., Sockets. This is more familiar to developers and allows many existing software packages/libraries to be used without modification.

c) **Standard Stacks –** Many years and tears have gone into optimizing TCP. We don't want to reinvent and/or debug this. Furthermore, many networks do not allow the use of UDP.

d) **Security –** We want to use SSL with standard interfaces and X.509 certificates. We don't want to have to re-invent this complex wheel, either.

e) **Mobility –** We want peers to communicate with each other even though they move from network to network. Often these networks are not controlled by the user who cannot reconfigure the NAT to add port mappings, allow UDP, or turn on UPnP.

4. Our Approach

Our approach is called NatTrav. In NatTrav, "recipient" peers willing to receive connections from "initiator" peers register with an intermediate connection broker by providing a network address and a URI – a Universal Resource Indicator to identify uniquely the recipient peer.

Connection brokers facilitate connections to recipients by (i) providing the current network address for the recipient and (ii) facilitating NAT Traversal if the recipient is NATed. Connection brokers are replicated for availability and scalability. See Figure 1.

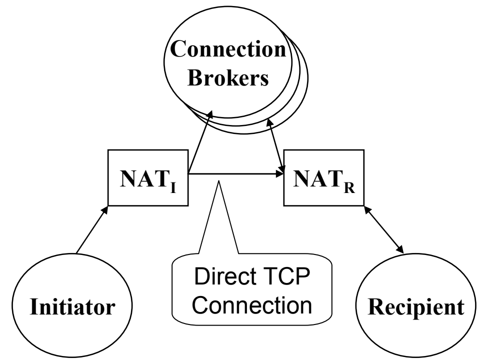
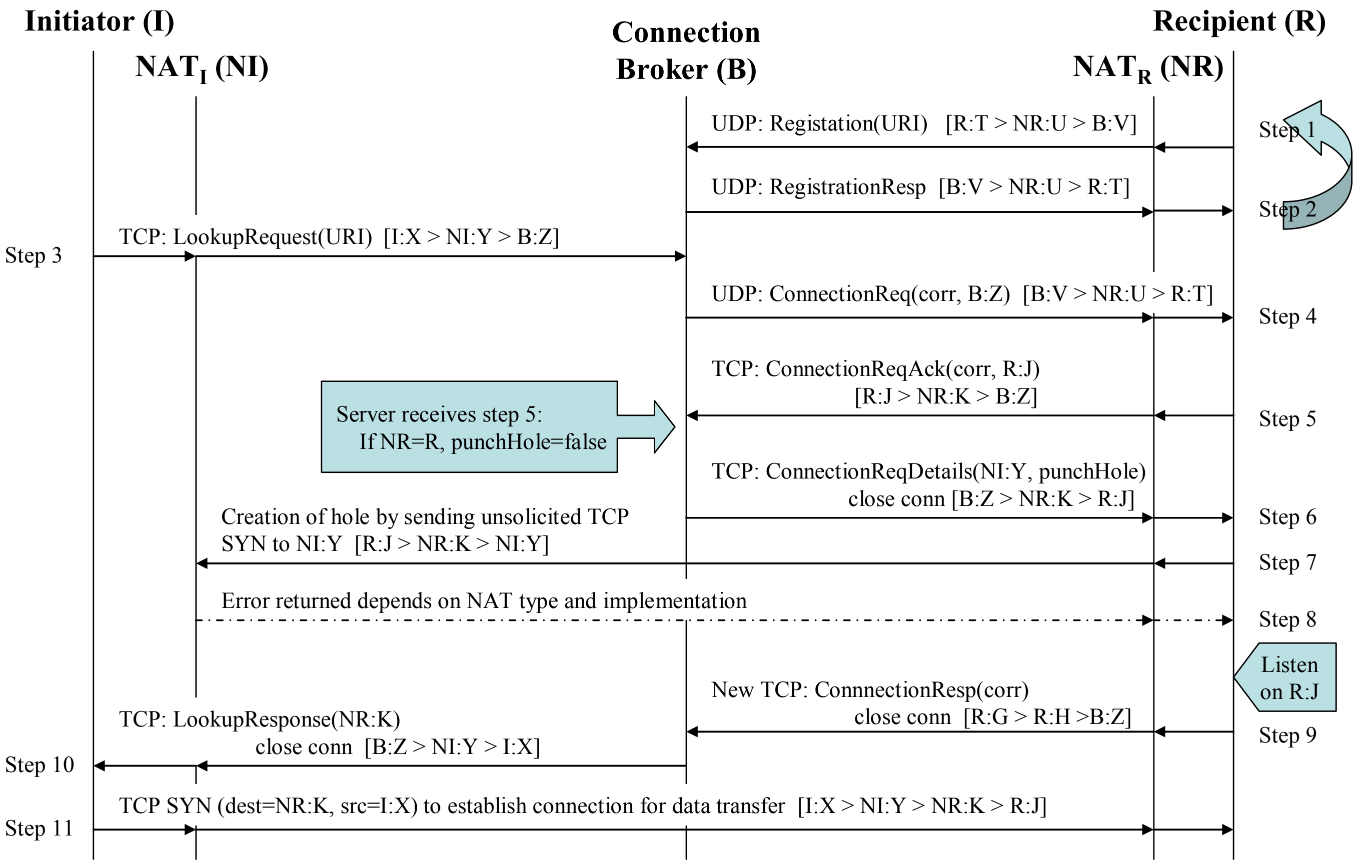


Figure 1: NatTrav Architecture

The NAT Traversal Protocol for cone-type mappings is shown in Figure 2. It may be possible to use port prediction to extend our solution to symmetric mappings as described by [16] in Section 7, but recent studies show that NAT boxes in the retail market place rarely use symmetric mappings [10].[†] Since Internet phones also do not work well on NAT boxes that create symmetric mappings, we believe that the industry is moving away from this approach.

Recipient Registration – In Steps 1 & 2, a recipient peer registers with a connection broker providing its URI name. It can either use UDP or TCP for registering. Using UDP (as shown in Figure 2) permits large numbers of recipients to register with each connection broker, however recipients must regularly send these Registration messages to the connection broker so that the connection broker can subsequently be able to send Connection Request messages to the Recipient through its NAT (Step 4). Using TCP for registration would normally require connection brokers maintain large numbers of open TCP sessions. Not shown in the figure, we can deputize UDP-capable recipients to act as proxies. (In true P2P fashion, each TCP-only recipient uses NatTrav as an initiator to set up TCP connections to proxies.)

[†] Of the 42 different versions of NAT boxes in the study, 4 do not follow the IETF Specification for NATs [2] and 1 always uses symmetric mappings. Of the remaining 37, including those dominant by retail market share, most use cone-type mappings all the time. A few use cone-type mappings unless the port number is already in use by another computer behind the NAT in which case they revert to creating a symmetric mapping. In this scenario, NatTrav fails to connect, but our when applications retry, NatTrav uses different ports and likely succeeds.



Note: The IP addresses and ports used for communication are shown in square brackets. For example: [I:X > NI:Y > B:Z] denotes communication from the Initator's IP address I and port X to the connection broker's IP address B on port Z via NAT_I's public address NI and public port Y.

Figure 2: NAT Traversal Protocol

Lookup – In Step 3, when an initiator peer wants to make a TCP connection to a recipient peer, it sends a Lookup Request to a connection broker. The connection broker eventually replies (Step 10) with a public IP address and port that the initiator can use (in Step 11) for a direct TCP connection from initiator to recipient (via their NAT boxes) as shown in Figure 1.

The connection broker checks to see if there is an active registration for the recipient. The connection broker may need to contact other connection brokers to determine this. If so, it sends a Connection Request to the recipient on the UDP address and port the recipient (or its proxy) used to register (Step 4). The Connection Request contains a correlator (corr) to track which Lookup Request subsequent steps are working on and the IP address and port of the connection broker that the recipient should use for the subsequent steps.

Punching the Hole – In Steps 5 & 6 the recipient uses TCP to exchange network address information with the connection broker specified in the Connection Request. The connection broker compares the recipient's private IP address (`R`) and its public IP address (`NR`). If they match, the recipient is not NATed. If they do not match, the recipient is NATed and the recipient is told to punch a hole in its NAT for messages coming from the initiator's public IP address and port (`NI:Y`).

```
public class NatTravSocket extends Socket {
    public NatTravSocket(String connectionBrokerName,
                         String recipientURI) throws IOException {
        // Implementation
    }
}
```

Figure 3: Java Class to Initiate a TCP Connection to a Recipient Peer

```
public class NatTravServerSocket {
    public NatTravServerSocket(String connectionBrokerName,
                               String myURI) throws IOException {
        // Implementation
    }

    public Socket accept() throws IOException {
        // Implementation
    }
}
```

Figure 4: Java Class to Receive TCP Connections from Initiator Peers

The trick here is that we use the same IP addresses and ports for TCP communication with the connection broker and for the direct TCP connection between initiator and recipient. Because we are punching holes in cone-type NATs, we know that the NATs will use the same proxy ports for communication with the connection broker and the peers. In the example shown in Figure 2, the initiator uses port `X` when communicating with the connection broker (Step 3), but the connection broker sees it coming from NAT_I's port `Y`. Similarly, the recipient uses port `J` (Step 5) and the connection broker sees NAT_R's port `K`. To punch the hole, the recipient closes its TCP connection with the connection broker used in Steps 5 & 6 and in Step 7 uses port `J` to attempt to open a TCP connection to `NI:Y`. Depending on the type and implementation of NAT_I, Step 8 may be a timeout, a TCP reset response, or (if NAT_I is a full-cone NAT) a port-in-use error (because NAT_I forwarded the TCP SYN on to `I:X`). In any case, the TCP connection will not succeed but the attempt enables NAT_R to forward communication from `NI:Y` sent to `NR:K` on to `R:J`.

Between Steps 8 & 9, we set up a `ServerSocket` to listen on `R:J`. Then we send a Connection Response message to the connection broker (Step 9). In Step 10, the connection broker tells the initiator that it can now set up a direct TCP connection to the recipient (via the NAT boxes) by using `NR:K`. In Step 11, the TCP connection is set up.

Our P2P applications use a Java package called `nattrav`. The `nattrav` package contains classes that parallel the style of the standard Java class libraries for setting up TCP Sockets between applications. Not only this, but the objects returned by the `nattrav` package are instances of the standard Java `Socket` class directly connecting the initiator and recipient peers. Figures 3 & 4 are code excerpts showing the interfaces for the most basic methods.

5. Security Extensions

In many cases, we want our P2P applications to use SSL connections between the peers. This is for privacy of the communication and to authenticate the peers. We use our own certification authority (CA) to sign X.509 certificates for connection brokers and the peers. The CA's signing certificate is preinstalled into our applications' key stores. We can then use the signed X.509 certificates to make SSL connections in Figure 2, Step 11.

The interesting security problem for our NAT Traversal Protocol as shown in Figure 2 is that nothing prevents a rogue peer from registering as a recipient thereby redirecting Connection Requests to itself. To guard against this, we also have developed a secure registration protocol that uses the X.509 certificates (and the corresponding private keys) to implement a simple challenge/response to authenticate connection brokers and recipients during registration.

6. Evaluation

To date, we have built two P2P applications using NatTrav: (1) a Remote Desktop Proxy that allows Remote Desktop Connections to Windows machines located by URI, and (2) a replicated, incremental backup service. At the time of this writing, these applications are in limited deployment.

In these deployments, the observed elapsed time to setup a TCP connection from an initiator to a recipient using NatTrav ranges from 1.1 to 21.2 seconds depending on many factors, including the speed of the network between the computers and the behavior of NAT_I in Step 8 of the protocol. The initial connection time was no problem for the more often used backup application as the replication occurs in the background.

Upon further investigation, we added a configurable timeout when setting up the TCP connection in Step 7. We currently run with this timeout set to 2 seconds and have now seen connection times under 5 seconds in all cases observed.

We note that in both applications, the ability to have direct TCP connections between the peers is very important. We are using standard Java Socket (and SSL) classes for easy development and efficient network performance.

A test of a connection broker running on an 800 MHz laptop driven by simulated client loads processed over 5,000 UDP Registrations (Steps 1 & 2) per second. UDP recipients re-register every minute, so a connection broker should support about 300,000 recipients. This does not measure the cost of replication or occasional Lookup Requests and Connection Requests. We believe these costs to be minimal. Since connection brokers provide an application specific service, running connection brokers to support instances of our applications is not a significant cost.

7. Other Emerging Solutions

UPnP is a new standard to support the ability to plug devices into a home network [11]. An application could use UPnP to configure a NAT box to forward to it incoming requests received on specific ports (thereby achieving NAT Traversal). Unfortunately, early UPnP implementations had highly publicized security issues and many NAT boxes that support UPnP ship with it turned off by default. Furthermore, UPnP enables any application on the LAN to create port mappings. Many savvy consumers continue to have security concerns. Anecdotally, we have found that WiFi hotspots tend not to enable UPnP. Users should not have to reconfigure their NAT boxes to turn on UPnP as they may not be technically capable, might not have administrative access, or their NAT might not support UPnP.

Nevertheless, UPnP support can be easily added to NatTrav. When available, recipients would use UPnP to configure port mappings on the NAT. The recipient would register the NAT's public IP address and a mapped port with a connection broker. Lookup Requests would still be used to find these recipients.

IPv6 is a new standard that specifies 128 bit IP addresses [12]. It is possible that the new, longer IPv6 addresses will reduce the need for NAT boxes; however we are skeptical. NAT boxes abound as IPv6 adoption has been slow and there is an expectation that protocol translating NAT boxes (NAT-PT) will be used to bridge between IPv4 and IPv6 networks. Other projects such as [13] are working on general solutions for NAT Traversal without any application changes, but they require deployment of significant additional network infrastructure.

SIP is a new IETF Session Initiation Protocol that can be used to initiate UDP connections for telephony and multimedia applications [14]. Except for security and NAT Traversal, it standardizes the communication formats for functions similar to our connection brokers. We chose not to use SIP because: (i) it has a tremendous amount of mechanism we do not need for our application, (ii) it does not provide NAT Traversal, and (iii) beyond standardizing how user ids and passwords are sent, it does not address our security concerns. Even if we were to include all the above capabilities in a SIP implementation, whether or not we use SIP internally in our applications is transparent to our users.

NUTSS is a new research project at Cornell [15]. As its acronym suggests, it proposes to combine **N**AT Traversal, **U**RIs, **T**unnelling over UDP, **S**IP, and **S**TUN. STUN [3] is a UDP-based Protocol that an application can use to talk with intermediate STUN servers to determine if it is NATed and if so, via what type of NAT. Again, we have several concerns about tunneling over UDP. Recently, the NUTSS researchers have proposed a TCP based approach [16] consisting of (i) STUNT: TCP extensions to STUN, and (ii) a TCP hole punching protocol. Their hole punching protocol is much more complex than ours requiring use of port prediction, STUNT, spoofing, and sending TCP SYNs with low TTLs. However, they are attempting to traverse symmetric NATs.

8. Conclusions

Our P2P applications require direct TCP connections between peers. By using a NAT Traversal solution, such as NatTrav, we are able to directly connect our peers across cone-type NATs: (i) using standard TCP Socket and SSL packages, (ii) with minimal cost per new peer, (iii) without routing through non-NATed peers, (iv) without requiring users to reconfigure their NATs, and (v) locating specific peers wherever they are connected to the Internet.

While we could not afford to wait for prevalent UPnP utilization and IPv6 deployment (which may never happen) or the future standardization activities initiated by NUTSS, we look forward to their future successes. Should support for symmetric NATs become important to our applications, NUTSS may be very important to us. As NAT box makers start supporting UPnP and enabling it by default, it may be useful to add UPnP support to our arsenal.

A final note: our NAT Traversal solution is application specific. So is Skype's approach of routing calls through non-NATed peers. Their approach works well because it's a low bandwidth application (less than 16 kbps during a call with custom encryption) [17]. But they likely will need to use direct TCP connections when they add video.

9. Acknowledgements

Special thanks to Mukund Gopalan and Kamal Saurabh who, with the author, created algorithms and their implementation for NAT Traversal described herein.

References

[1] K. Egevang & P. Francis. The IP Network Address Translator (NAT). IETF RFC 1631.
[2] P. Srisuresh & K. Egevang. Traditional IP Network Address Translator. IETF RFC 3022.
[3] J. Rosenberg, et al. STUN - Simple Traversal of User Datagram Protocol Through Network Address Translators. IETF RFC 3489.
[4] T. Jessup. How Kazaa Works. Utah Education Network Summit, Oct 2003. (http://www.ndnn.org/blog/downloads/summit/UENSummit_Peer_2_Peer.ppt)
[5] Lime Wire LLC. Frequently Asked Questions. (http://www.limewire.com/english/content/faq.shtml)
[6] BitTorrent. FAQ. (http://bittorrent.com/FAQ.html)
[7] Groove Networks. Groove Web Services. Nov 2002. (http://www.groove.net/pdf/wp-groove_web_services.pdf)
[8] Skype Technologies S.A. Skype Explained. (http://www.skype.com/products/explained.html)
[9] Newrong Inc. NAT Traversal SDK. (http://www.newrong.com/en/product/index.html)
[10] C. Jennings. NAT Classification Results using STUN. IETF Internet Draft. Oct 2004. (http://www.ietf.org/internet-drafts/draft-jennings-midcom-stun-results-02.txt)
[11] T. Fout. Universal Plug and Play in Windows XP. Microsoft Corporation.
[12] S. Deering & R. Hinden. Internet Protocol, Version 6 (IPv6) Specification. IETF RFC 2460. Dec 1998.
[13] T.S. Ng, et al. A Waypoint Service Approach to Connect Heterogeneous Internet Address Spaces. USENIX Annual Technical Conference, Boston, MA, Jun 2001.
[14] J. Rosenberg, et al. SIP: Session Initiation Protocol. IETF RFC 3261. Jun 2002.
[15] P. Francis. Is the Internet Going NUTSS? IEEE Computing, Nov-Dec 2003.
[16] S. Guha, et al. NUTSS: A SIP-based Approach to UDP and TCP Network Connectivity. SIGCOMM'04 Workshops, Aug 2004.
[17] Skype Technologies S.A. Skype Technical FAQ. (http://www.skype.com/help/faq/technical.html)