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Abstract

The pluggable transports model in Tor separates the concerns of anonymity and circumvention by running circumvention code in a separate process, which exchanges information with the main Tor process over local interprocess communication. This model leads to problems with scaling, especially for transports, like meek and Snowflake, whose blocking resistance does not rely on there being numerous, independently administered bridges, but which rather forward all traffic to one or a few centralized bridges. We identify what bottlenecks arise as a bridge scales from 500 to 10,000 simultaneous users, and then from 10,000 to 50,000, and show ways of overcoming them, based on our experience running a Snowflake bridge. The key idea is running multiple Tor processes in parallel on the bridge host, with externally synchronized identity keys.

1 Introduction

Bridges and pluggable transports are how Tor adds blocking resistance (censorship circumvention) to its core function of anonymity. Bridges are relays whose network addresses are not globally known, meant to be difficult for a censor to discover and block by address. Pluggable transports are modular tunneling protocols that encapsulate and disguise an inner protocol, thereby preventing a censor from recognizing the Tor protocol and blocking connections on that basis.

Tor's original blocking resistance design called for a large number of "bridge" relays [3 §5], to which clients would connect directly, using the ordinary TLS-based Tor protocol. The difference between ordinary relays and bridges was only that the network addresses of bridges are not made public in the Tor consensus, but rather distributed one at a time, in a controlled fashion. The blocking resistance of this model depends on keeping bridge addresses secret, because there is nothing to stop a censor from blocking a bridge by its address, once known. When pluggable transports arrived on the scene, many adopted the same strategy with respect to address blocking resistance. obfs2, obfs3, FTE, ScrambleSuit, obfs4—all these change the protocol between client and bridge, but they retain the model of clients making TCP connections to fixed bridge IP addresses that must be kept secret. Because this model requires a large pool of bridges, it naturally achieves "horizontal" scaling, with user traffic being distributed over hundreds of independently operated hosts in different networks.

But other pluggable transports are not based on a model of secret bridge addresses: meek and Snowflake are currently deployed pluggable transports whose resistance to address-based blocking comes about in other ways. In these transports, the host that is the gateway to the Tor network (the "bridge" proper) is decoupled from the means of accessing it, which is rather via some intermediary (a CDN in meek; a temporary browser proxy in Snowflake). Transports like these do not benefit, in terms of blocking resistance, from having a large number of bridges, and it is therefore convenient to run just one, centralized bridge—whose address does not need to be secret—to receive all the transport's traffic. This, however, requires attention to the "vertical" scaling of the bridge.

In this paper, we show how to do this vertical scaling of a pluggable transports Tor bridge. The key technique is to run multiple Tor processes on the same host with the same identity keys. This alleviates the largest single bottleneck, namely that of a single Tor process being CPU-limited, but also gives rise to a few complications. Beyond that, there are other resource constraints to consider, such as limits on file descriptors and ephemeral port numbers. The recommendations come from our experience running a Snowflake bridge from December 2021 to February 2023, during which time the average number of simultaneous users grew from 2,000 to around 100,000.

2 Background on pluggable transports

The Pluggable Transports specification [10] describes how Tor interacts with pluggable transports. It is built on a model of separate processes and interprocess communication. The Tor process spawns a child process; the pluggable transport process reports status on its standard output stream; and there-

after user traffic is carried over localhost TCP connections.[1] Refer to Figure 1. Client and server transports work similarly, but only the server side concerns us here.

Pluggable transports are enabled in Tor's configuration file, torrc. A sample configuration for a transport called "mypt" looks like this:

```
ServerTransportPlugin mypt exec /usr/local/bin/mypt
ServerTransportListenAddr mypt 0.0.0.0:1234
ExtORPort auto
```

When Tor starts a pluggable transport, it passes configuration information to the subprocess in environment variables. The above torrc causes Tor to execute /usr/local/bin/mypt as a subprocess, with the following variables set in its environment (*eph* is a random ephemeral port):

```
TOR_PT_SERVER_TRANSPORTS=mypt
TOR_PT_SERVER_BINDADDR=mypt-[::]:1234
TOR_PT_EXTENDED_SERVER_PORT=127.0.0.1:eph
TOR_PT_AUTH_COOKIE_FILE=
↪ /var/lib/tor/extended_orport_auth_cookie
```

`TOR_PT_SERVER_TRANSPORTS` tells the pluggable transport what named transports to start (because one executable may support multiple transports). `TOR_PT_SERVER_BINDADDR` is the address at which the pluggable transport should listen for incoming connections (if such a notion makes sense for the transport). `TOR_PT_EXTENDED_SERVER_PORT` is the TCP address of Tor's Extended ORPort [6], the interface between the pluggable transport and the ordinary Tor network. The pluggable transport process receives connections from the Internet, removes the obfuscation layer, and forwards the tunneled stream to the Extended ORPort of the Tor process. The Extended ORPort supports a meta-protocol to tag incoming connections with a client IP address and a transport name, which is used by Tor Metrics to provide country- and transport-specific metrics. `TOR_PT_AUTH_COOKIE_FILE` is a path to a file containing an authentication secret that is needed when connecting to the Extended ORPort—synchronizing this secret across multiple instances of Tor will be one of the complications to deal with in the next section.

3 Multiple Tor processes

The first and most important bottleneck to overcome is the single-threaded Tor implementation.[2] A single Tor process is limited to one CPU core: once Tor reaches 100% CPU, the performance of the bridge is capped, no matter the speed of the network connection or the number of CPU cores to spare. For us, this started to be a problem at around 6,000 simultaneous users and 10 MB/s of Tor bandwidth.

[1] The Pluggable Transports 2.x and 3.x specifications [8], which descend from Tor's version 1 specification, define an "API" interface for linking pluggable transports directly into an application, in addition to the Tor-like "IPC" interface. Tor does not use or support these later specifications.

[2] It is expected that Arti, the in-progress reimplementation of Tor, will be natively multi-threaded, which will remove this primary complication.

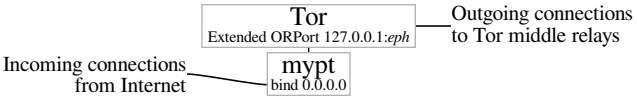

Figure 1: The normal way of running a server pluggable transport. The init system spawns a Tor process, which in turn spawns a pluggable transport process. This model reaches a performance plateau when the Tor process saturates one CPU.

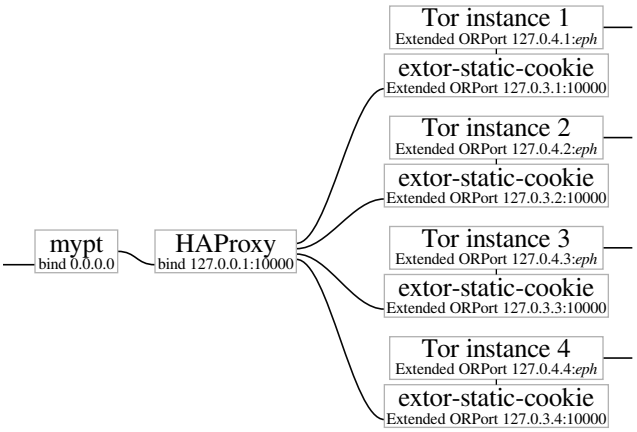

Figure 2: Our multi-Tor setup that permits better scaling. The init system spawns multiple independent Tor processes and a load balancer to distribute traffic over them. The pluggable transport process is no longer a child of a Tor process, but is spawned by the init system directly. The pluggable transport process communicates upstream with the load balancer, which makes the Tor instances' several Extended ORPorts appear as one. Each Tor process spawns an extor-static-cookie process (in the manner of Figure 1), in order to present a consistent Extended ORPort authentication secret through the load balancer.

Our solution is to run multiple Tor processes concurrently, and mediate the pluggable transport's access to them with a load balancer. (We use HAProxy, though any load balancer will do.) Refer to Figure 2. As many Tor processes can be run as are needed to distribute CPU load; we started with 4 and now use 12. The several Tor instances are independent, in the sense that they do not communicate with one another; but they all share the same long-term identity keys, so they are equally capable of serving as the first hop in a Tor circuit for a client that expects a certain bridge fingerprint. The pluggable transport server receives incoming connections, as before, but instead of forwarding connections to the Extended ORPort of a single Tor process, it sends them to the load balancer, which then forwards to one of the many Tor processes. The extor-static-cookie component paired to each Tor process resolves a complication that will be explained in Section 3.1.

This multi-instance arrangement requires subverting the usual pluggable transports subprocess model of Section 2.

Normally, the operating system's init system (e.g. systemd) starts Tor, and Tor starts the pluggable transport server. Here, we have the init system start the pluggable transport server, the load balancer, and all the instances of Tor as sibling processes. We set up the environment of the pluggable transport server as if it had been started by Tor in the normal way, but we make `TOR_PT_EXTENDED_SERVER_PORT` point to the load balancer, rather than to any particular instance of Tor. (See Appendix A for sample systemd and other configuration files.)

On Debian or Ubuntu, the tor-instance-create utility [7] is a convenient way to create and manage multiple instances of Tor with independent configuration files:

```
tor-instance-create mypt1
tor-instance-create mypt2
tor-instance-create mypt3
tor-instance-create mypt4
```

Each instance exposes an Extended ORPort interface on a distinct, static localhost address. Those Extended ORPort addresses are listed in the load balancer configuration file.

To make the instances all have the same identity keys, start and stop one of them to make it generate keys for itself:

```
systemctl start tor@mypt1
systemctl stop tor@mypt1
```

Then copy that instance's "keys" subdirectory into the data directory of the other instances, fixing permissions as necessary. This causes the instances to be interchangeable, in terms of being able to build circuits under the shared bridge fingerprint.

With multiple instances of Tor created and their identity keys replicated, there are just a few more details to look after.

3.1 Extended ORPort authentication

The Extended ORPort protocol begins with an obligatory authenticated handshake. Both Tor, and the pluggable transport that connects to it, cryptographically verify that the other has access to a secret "cookie" stored in a file [6 §2.1]. Tor regenerates the cookie file every time it is restarted, and shares the path to the file with pluggable transports in the `TOR_PT_AUTH_COOKIE_FILE` environment variable. This poses a problem for the multi-instance Tor setup. Since every instance of Tor generates its cookie file independently, and the pluggable transport cannot predict which instance it will be connected to through the load balancer, it does not know what Extended ORPort authentication secret to use.

Tor does not expose a configuration option to control or disable the regeneration of authentication cookie files. We need a way to expose an Extended ORPort interface with a uniform authentication secret across all Tor instances. To do this, we insert an adapter, called extor-static-cookie [11], between the load balancer and the actual Extended ORPort of each of the Tor processes. The adapter acts as an Extended ORPort *client* towards its parent Tor process, and an Extended ORPort *server* towards the load balancer (and the server pluggable transport in turn). As a client, extor-static-cookie communicates with its instance of Tor using the authentication cookie specific to that instance. As a server, it uses a static authentication cookie file that is also made available to the server pluggable transport in its `TOR_PT_AUTH_COOKIE_FILE` environment variable. The copies of extor-static-cookie are spawned using the normal pluggable transports subprocess machinery of Section 2. Extended ORPort authentication does not serve a security purpose, so working around it in this way poses no risk.

Besides its brief intercession at the beginning of each connection, extor-static-cookie does nothing but sit in the communications pipeline and consume CPU resources. It would be better to do away with it entirely. We hope a future version of Tor or Arti will offer an alternative authentication scheme that is more compatible with pluggable transport processes not managed by Tor, or even just an option to disable re-randomization of Extended ORPort authentication cookies. We considered a few alternative solutions to the problem of Extended ORPort authentication. It would be easy to patch Tor to use a hardcoded cookie, say, but maintaining a fork would complicate the deployment of security updates, which we deemed unacceptably risky. In place of the Extended ORPort, it is possible to use the regular, non-extended ORPort, which does not have any kind of authentication. But the regular ORPort does not have a way to tag connections with a client IP address or transport name, which would mean the loss of country- and transport-specific metrics.

3.2 Disabling onion key rotation

Besides its identity key, which never changes, a Tor relay or bridge has medium-term onion keys that are used in circuit construction [4 §4]. Onion keys are rotated on a fixed schedule (every 28 days, as of 2023). Tor clients cache a bridge's onion public keys when they connect; subsequent connections only work if the cached keys are among the bridge's two most recently used sets of onion keys. Immediately after being created, our multiple Tor instances have identical onion keys, because of the manual copying operation. But without further arrangements, the instances would eventually independently rotate their onion keys, which would cause later circuit creation attempts to fail.

To prevent this divergence, we disable onion key rotation. Tor does not expose a configuration option for this, so we resort to external means. We create preexisting directories at the filesystem paths that Tor uses as the destination of file rename operations during key rotation, secret_onion_key.old and secret_onion_key_ntor.old. (Preexisting *files* are not good enough; they must be directories to stop the rename operation from succeeding.) Tor logs an error every time thereafter that it tries and fails to rotate its onion keys, but otherwise continues running with the same keys.

The security consequences of onion key compromise, in the

worst case, would be that an attacker could impersonate the bridge in future Tor circuits, but still would not be able to decrypt past traffic. The upshot is that we must protect the now long-term onion keys as carefully as identity keys.

4 Further bottlenecks

Distributing Tor processing over many CPU cores is the essential step to enable scaling. As the number of users increases, the bridge will begin to bump into other, less restrictive limitations.

File descriptor limits. Every open socket consumes a file descriptor. Because the pluggable transports model uses sockets not only for external connections but also for interprocess communications, and the number of sockets is proportional to the number of users, it is easy to exceed the operating system's default limit on the number of file descriptors. This manifests in error messages like "too many open files." Tor and HAProxy automatically override the defaults and set sufficiently high limits for themselves, but for the server pluggable transport process you can use, for example, `LimitNOFILE` in a systemd service file to raise the limit (see Section A.2). For us, a limit of 64 thousand was insufficient, but we have not had problems since raising the limit to 1 million.

Ephemeral TCP ports. TCP sockets are distinguished from one another by a four-tuple consisting of the source and destination IP addresses and the source and destination port numbers. When connecting a socket, the operating system chooses a port number from the ephemeral port range to serve as the socket's source port. If all ephemeral ports are already in use, such that the socket's four-tuple would not be unique, the connection fails with an error like "cannot assign requested address."

The baseline mitigation for ephemeral port exhaustion is expanding the range of ephemeral ports. On Linux, it looks something like this:

```
sysctl -w net.ipv4.ip_local_port_range="15000 64000"
```

But this alone is not enough for a pluggable transports bridge. The bridge's outgoing connections to other Tor relays are not the main problem—the same source port can be used in many sockets, as long as the destination addresses are different. The real crunch comes from the bridge's many localhost TCP connections, the internal links in Figure 2. If source and destination IP addresses are both 127.0.0.1, source and destination port numbers are all that remain to make TCP sockets distinct.

Part of the solution is using different localhost IP addresses for different server sockets. Not only 127.0.0.1, but the entire 127.0.0.0/8 range is dedicated to localhost [1 §2.2.2]. We use 127.0.0.1 for HAProxy, but 127.0.3.*N* for the *N*th instance of extor-static-cookie, and 127.0.4.*N* for the *N*th Tor instance's Extended ORPort. This provides some variation in the destination addresses of socket four-tuples, but it still is not enough: we must also diversify source addresses. In HAProxy we use the `source` option to use 127.0.2.*N* as the source address when connecting to the *N*th instance of extor-static-cookie (see Section A.3); this expands the number of possible simultaneous connections by a factor equal to the number of Tor instances. For the bottleneck connection between the pluggable transport and the load balancer, we added a custom option `orport-srcaddr` to the pluggable transport (Section A.2); that instructs it to choose a random source address in the 127.0.1.0/24 range when connecting to the load balancer, which increases the number of usable source addresses by a factor of 256. The extor-static-cookie adapter also supports the `orport-srcaddr` option (Section A.1), which we set to use the range 127.0.5.0/24, though it is less necessary there, since each instance of extor-static-cookie sees only a $1/N$ fraction of all connections.

Firewall connection tracking. The connection tracking (conntrack) feature of the Linux firewall has a default limit of 262,144 connections in Linux 5.15. When the number of connections reaches that limit, new connections will be dropped. Our experiments showed that the number of connections was getting close to the limit during the busiest times of day, so we doubled the size of the connection tracking table:

```
sysctl -w net.netfilter.nf_conntrack_max=524288
sysctl -w net.netfilter.nf_conntrack_buckets=524288
```

5 Discussion

The multiple-Tor architecture described in this paper may be useful also for non–pluggable transport relays, such as large exit relays. We hope, though, that a future version of Tor or Arti will make our workaround obsolete.

The pluggable transports model of interprocess communication over TCP sockets is suitable for clients and low- to medium-use servers, but it starts to become awkward for high-use servers, principally because of TCP ephemeral port exhaustion. Future designs should consider alternatives, such as Unix domain sockets, or the in-process API of later pluggable transports specifications [8].

The architecture described in this paper will allow full use of server hardware, but hardware is still the ultimate limiter. In Snowflake, we are now in a situation where we have exhausted the capacity of one bridge server. In order to continue scaling, we have had to deploy a second Snowflake bridge on separate hardware. This is partly because Snowflake is a particularly demanding server pluggable transport, requiring much RAM and CPU (more than the Tor processes). A less complex server transport would be able to support more users on the same hardware.

Acknowledgements

The basic architecture described in this paper was worked out in a thread on the tor-relays mailing list [5]. We thank Roger Dingledine for confirming that running multiple instances of Tor with synchronized identity keys would be feasible, suggesting a similarity with the "router twins" [2] concept from the early history of Tor, and anticipating the problem of onion key rotation. Nick Mathewson answered questions about onion keys and future development plans. Silvia Puglisi and Georg Koppen enhanced Tor Metrics to be aware of relays that publish multiple independent descriptors for the same relay fingerprint [9]. Greenhost provided hosting for the Snowflake bridge during the initial transition to the load-balanced configuration. We thank donors and financial supporters: particularly the Open Technology Fund, for a short-term grant to support operational costs when we moved the bridge to a dedicated server; Mullvad VPN, for a donation of hardware for the new server; and OBE.NET, for providing hardware colocation and at-cost bandwidth.

Availability

Step-by-step instructions for installing a load-balanced bridge configuration for Snowflake are available in the Tor anti-censorship team's Snowflake Bridge Installation Guide: https://gitlab.torproject.org/tpo/anti-censorship/team/-/wikis/Survival-Guides/Snowflake-Bridge-Installation-Guide.

The extor-static-cookie adapter program is available from https://gitlab.torproject.org/tpo/anti-censorship/pluggable-transports/extor-static-cookie.

The home page of this article is https://www.bamsoftware.com/papers/pt-bridge-hiperf/. It has the source code of the article as well as any updates.

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A Configuration files

A.1 Per-instance torrc files

This is a template for per-instance torrc configuration files. If using tor-instance-create [7] with instance name prefix "mypt", the file for instance *N* will be at the path /etc/tor/instances/mypt*N*/torrc. Replace the highlighted text with appropriate values. *NICKNAME* and *EMAIL* are the same for all instances; *N* is the instance number. It is important to give every instance a distinct nickname, because that is how Tor Metrics disambiguates multiple descriptors with the same relay fingerprint.

The `orport-srcaddr` transport option is not a universal standard; it is a special feature in extor-static-cookie to avoid ephemeral port exhaustion as described in Section 4. When connecting to the Tor process's Extended ORPort, extor-static-cookie will choose a random source IP address in the range 127.0.5.0/24.

```
BridgeRelay 1
AssumeReachable 1
BridgeDistribution none
ORPort 127.0.0.1:auto # unused
ExtORPort 127.0.4.N:auto
SocksPort 0
ServerTransportPlugin mypt exec extor-static-cookie /etc/extor-static-cookie/static_extended_orport_auth_cookie
ServerTransportListenAddr mypt 127.0.3.N:10000
ServerTransportOptions mypt orport-srcaddr=127.0.5.0/24
Nickname NICKNAMEN
ContactInfo EMAIL
```

A.2 Pluggable transport systemd service file

Install this file as /etc/systemd/system/mypt.service. Enable it with `systemctl enable mypt` and use `systemctl start mypt` to start it running. The service file assumes the existence of a user called "mypt" (`adduser --system mypt`).

The `Environment` variables set up a simulated pluggable transports environment, with `TOR_PT_EXTENDED_SERVER_PORT` pointing at the load balancer. *PORT* is the pluggable transport server's external listening port. As with extor-static-cookie, the `orport-srcaddr` transport option whose purpose is to conserve ephemeral ports is a special addition we have implemented, not a part of pluggable transports or any other standard.

```
[Unit]
Description=DESCRIPTION

[Service]
Type=exec
Restart=on-failure
User=mypt
StateDirectory=mypt
LogsDirectory=mypt
# Use CAP_NET_BIND_SERVICE if the server needs to bind to a privileged port.
AmbientCapabilities=CAP_NET_BIND_SERVICE
NoNewPrivileges=true
ProtectHome=true
ProtectSystem=strict
PrivateTmp=true
PrivateDevices=true
ProtectClock=true
ProtectKernelModules=true
ProtectKernelLogs=true
LimitNOFILE=1048576
Environment=TOR_PT_MANAGED_TRANSPORT_VER=1
Environment=TOR_PT_SERVER_TRANSPORTS=mypt
Environment=TOR_PT_SERVER_BINDADDR=mypt-[::]:PORT
Environment=TOR_PT_EXTENDED_SERVER_PORT=127.0.0.1:10000
Environment=TOR_PT_AUTH_COOKIE_FILE=/etc/extor-static-cookie/static_extended_orport_auth_cookie
Environment=TOR_PT_SERVER_TRANSPORT_OPTIONS=mypt:orport-srcaddr=127.0.1.0/24
Environment=TOR_PT_STATE_LOCATION=%S/mypt/pt_state
Environment=TOR_PT_EXIT_ON_STDIN_CLOSE=0
ExecStart=/usr/local/bin/mypt

[Install]
WantedBy=multi-user.target
```

A.3 HAProxy configuration file

The below configuration defines a frontend listener at 127.0.0.1:10000, which forwards to a backend consisting of the multiple Tor instances (actually their extor-static-cookie adapters). Each backend connection uses a different source IP address, to help conserve ephemeral ports. There is no need for any kind of backend affinity; simple round-robin balancing is sufficient. This configuration should be added to any defaults already present in /etc/haproxy/haproxy.cfg.

```
frontend tor
        mode tcp
        bind 127.0.0.1:10000
        default_backend tor-instances
        option dontlog-normal
        timeout client 600s
backend tor-instances
        mode tcp
        timeout server 600s
        server mypt1 127.0.3.1:10000 source 127.0.2.1
        server mypt1 127.0.3.2:10000 source 127.0.2.2
        server mypt1 127.0.3.3:10000 source 127.0.2.3
        server mypt1 127.0.3.4:10000 source 127.0.2.4
```