Tor's Been KIST: A Case Study of Transitioning Tor Research to Practice

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Abstract

Most computer science research is aimed at solving difficult problems with a goal of sharing the developed solutions with the greater research community. For many researchers, a project ends when the paper is published even though a much broader impact could be achieved by spending additional effort to transition that research to real world usage. In this paper, we examine the opportunities and challenges in transitioning Tor research through a case study of deploying a previously proposed application layer socket scheduling policy called KIST into the Tor network. We implement KIST, simulate it in a 2,000-relay private Tor network using Shadow, deploy it on a Tor relay running in the public Tor network, and measure its performance impact. Confirming the results reported in prior research, we find that KIST reduces kernel outbound queuing times for relays and download times for low-volume or bursty clients. We also find that client and relay performance with KIST increases as network load and packet loss rates increase, although the effects of packet loss on KIST were overlooked in past work. Our implementation will be released as open-source software for inclusion in a future Tor release.

1 Introduction

Tor [2, 8] is the most popular system for anonymous communication, consisting of roughly 7,500 volunteer-operated *relays* transferring over 100 Gbit of traffic every second [3]. Tor has roughly two million unique daily users [3], over 500,000 of which use Tor at any given time [14]. Clients using Tor construct *circuits* of three Tor relays through which they tunnel their Internet connections, while a *hidden onion service* protocol allows both clients and servers to create circuits and connect them inside of the Tor network in order for both endpoints to achieve end-to-end encryption and anonymity.

Tor is designed to provide low-latency anonymity: relays immediately forward packets without introducing any artificial delays in order to provide a usable experience for clients that use Tor to browse Internet websites. However, Tor's three relay-hop design (six relay-hops for hidden onion services) combined with its popularity and available resources results in significantly longer transfer times compared to direct connections.

There has been a significant amount of research into performance enhancements for the Tor network [6], including proposals that change the way Tor relays classify [4, 15] and prioritize [12, 18] traffic and handle relay connections [5, 9, 10, 12, 16, 17]. Relays currently use the circuit scheduling approach of Tang and Goldberg [18]: an exponentially-weighted moving average (EWMA) of the throughput of each circuit is used to prioritize low-volume, bursty traffic over high-volume, bulk traffic. Jansen *et al.* identified flaws in the way that relays write data to the kernel that were significantly reducing the effectiveness of the intended priority mechanisms, and proposed a new socket scheduling policy called Kernel-Informed Socket Transport (KIST) to overcome these challenges [12]. A KIST prototype was evaluated in Tor network simulations using Shadow [1, 13] and was shown to reduce kernel outbound queuing times and end-to-end latency for low-volume traffic; however, it was never tested or evaluated on any relays running in the live, public Tor network.

In this paper, we present our work in further understanding the impact that KIST has on client and relay performance, with the goal of producing a production-level implementation of KIST that is suitable to include in a future Tor release. Toward this goal, we first independently implement KIST in collaboration with the Tor developers: we discuss the details of this implementation and the supporting architecture in Section 3. Our KIST implementation improves upon the previous prototype [12] by significantly reducing the overhead involved in managing the process of writing to sockets, and contains the components that would be required for our code to be included in Tor (e.g., unit tests and documentation).

We then simulate KIST in a large scale private Tor network of 2,000 relays and up to 70,000 clients using Shadow [1, 13], both to test our code and to confirm past research [12] reporting that KIST is capable of improving performance for Tor relays and clients. Our results in Section 4 confirm the results from prior work: KIST is capable of relocating congestion from the kernel output queue into Tor where it can be better managed and priority can be properly applied. Additionally, the effects of packet loss on KIST were not considered in prior research; we extend that research by analyzing KIST under a range of network load and packet loss models. We find that KIST performs at least as well as the default Tor scheduler across all tested conditions, and that KIST is able to increasingly improve both client and relay performance relative to Tor's default scheduler as both network load and packet loss rates increase. We provide the first indication that KIST effectively backs off of high-volume circuits under high loss while correctly prioritizing low-volume or bursty circuits.

We also provide the first live-network evaluation of KIST in Section 5, using a deployment of KIST on a fast relay in the public Tor network. We find that Tor application queuing time increases with KIST as expected; however, we are unable to detect a significant change in relay throughput or kernel outbound queuing time that can be attributed to KIST. We believe that this is partially due to our lack of experimental control over Tor network effects, and partially because our relay did not experience enough load or packet loss for KIST to significantly influence the socket scheduling process. We also find that KIST overhead is tolerable: with our optimizations and suggested parameter settings, the system call overhead scales linearly with the number of relay-to-relay TCP connections with write-pending data, and independently of the total number of open sockets.

Finally, we briefly discuss the lessons that we learned while producing and evaluating deployable Tor code, and generalize our experiences to provide insights into the process of transitioning Tor research.

2 Background

In this section we provide background on Tor and how it handles traffic, and describe how KIST changes Tor's scheduling mechanisms.

2.1 Tor

Tor [8] is a low-latency anonymity network that is primarily used to access and download webpages and to transfer files [14], but can be used to facilitate anonymous communication between any pair of communicating peers in general.

To use Tor, a client first constructs a *circuit* by telescoping an encrypted connection through an *entry* relay, a *middle* relay, and an *exit* relay, and then requests the exit relay to connect to the desired external destinations on the client's behalf. The logical connections made by clients to destinations are called *streams*, and they are multiplexed over circuits according to the policy set by each circuit's exit relay. The client and the exit relay package all application-layer payloads into 512-byte *cells*, which are onion-encrypted and forwarded through the circuit. When a client and a server communicate using the onion service protocol, they both construct circuits and connect them at a client-chosen rendezvous relay; the resulting six relay-hop circuit is then used to provide end-to-end encryption.

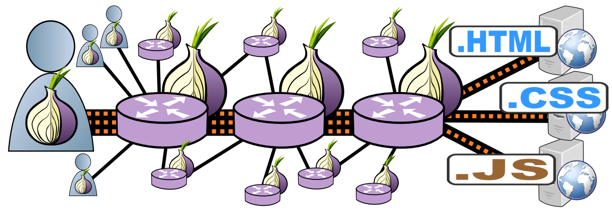


Figure 1: Connections between Tor clients, relays, and destinations. Solid black lines represent TCP connections, and dashed orange lines represent logical streams of client application payloads that are multiplexed over both the TCP connections and the encrypted circuits that are constructed by clients. High performance relays generally maintain thousands of open network sockets as a result of this architecture.

Circuits are multiplexed over TCP connections which are maintained between Tor clients, relays, and destinations (see Figure 1). During the circuit construction process, each relay will create a TCP connection to the next-hop relay chosen by the client if such a connection does not already exist. Although idle TCP connections are closed to conserve resources, each relay may maintain up to $n-1$ open TCP connections to other relays for onion routing in a network consisting of n relays. In addition to the relay TCP connections, entry relays maintain TCP connections with clients while exit relays initiate and maintain TCP connections with destination servers, e.g., to download webpages and embedded objects. Therefore, high-bandwidth relays generally maintain thousands of open network sockets at any given time.

2.2 Tor Traffic Management

We now describe how a Tor relay internally handles and forwards traffic prior to version `0.2.6.2-alpha`, i.e., before merging support for KIST. We describe how this architecture was modified to support KIST in newer versions of Tor in Section 3.

Tor's traffic handling process involves several layers of buffers and schedulers, and is driven by an event notification library called libevent[1] (see Figure 2). Tor registers new sockets with libevent and uses it to asynchronously poll those sockets in order to track when they are readable and writable. There is an input and output byte buffer corresponding to each socket that is used to buffer kernel reads and writes, respectively. There is also a circuit scheduler corresponding to each socket that is used to prioritize traffic, as we will further describe below.

When a TCP socket is readable, i.e., has incoming bytes that can be read from the kernel, libevent notifies Tor by executing a callback function (Figure 2🅐). Tor then reads input bytes from the readable TCP socket into

[1] `http://libevent.org`

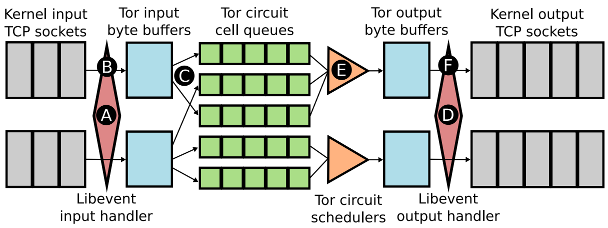


Figure 2: Data is transferred through Tor using several layers of buffers and queues. The transfer process is driven by libevent, an event notification library. Circuit schedulers attempt to prioritize low-volume or bursty traffic (web browsing) over high-volume, bulk traffic (file sharing).

the input byte buffer using OpenSSL, which removes the transport layer of encryption (Figure 2B). For each 512-byte chunk that accumulates in the input buffer, Tor creates a cell, applies onion encryption to it, and then either handles the cell directly if possible or moves it to the circuit queue corresponding to its next-hop relay (Figure 2C). The cells remain in the circuit queue until they can be written to the outgoing TCP connections.

When a TCP socket is writable, i.e., has available space such that outgoing bytes can be written to the kernel, libevent notifies Tor by executing a callback function (Figure 2D). Because circuits are multiplexed over TCP connections, there may be several circuits with cells that are pending to be written to the writable socket; there is a circuit scheduler corresponding to each socket that is used to determine the order that pending cells are written. The circuit scheduler corresponding to the writable socket is invoked to choose the circuit with the best priority and write a cell from it to the output byte buffer (Figure 2E). Tor uses the circuit scheduling algorithm of Tang and Goldberg [18] to determine circuit priority. Their algorithm is based on an exponentially-weighted moving average (EWMA) of circuit throughput and prioritizes circuits carrying low-volume or bursty traffic over those carrying high-volume, bulk traffic. Bytes from the output buffer are written to the kernel using OpenSSL (Figure 2F) when the output buffer length exceeds a threshold of 32 KiB and when circuit scheduling for the writable socket is complete.

Note that the entire reading and writing processes are driven by libevent, which issues readable and writable notifications for one socket at a time. The order in which these notifications are delivered is not configurable.

2.3 KIST

In prior work, Jansen *et al.* observed two major problems with Tor's traffic management process, and designed a new socket scheduler, called kernel-informed socket transport (KIST), to correct these issues [12].

Problem: Sequential Socket Writes: Because Tor only considers a single socket out of potentially thousands or tens of thousands of sockets at a time, it is possible that the circuit priority scheduler would only consider a small fraction of the circuits that could have been written at any given time. They showed through experimentation that circuit priority mechanisms are ineffective when multiple circuits of different priority levels do not share the same outgoing socket (since then they are not considered by the same circuit scheduler instance). Because of Tor's sequential, single-socket output handler, worse priority high-volume traffic from one socket would be written to the kernel before better priority low-volume traffic from another socket. Additionally, the first-in-first-out kernel scheduler would send the already-written worse-priority data before any better-priority data that may arrive and be written an instant later.

Solution: Global Circuit Scheduling: To correctly prioritize circuits, KIST modifies the way Tor responds to the libevent writable notifications. Rather than immediately scheduling circuits and writing cells, KIST instead adds the writable socket to a set of pending sockets. KIST continues collecting this set over a configurable time period in order to improve priority by increasing the number of candidate circuits whose cells may be written. At the end of the period, KIST chooses from the set of all circuits that contain cells that are waiting to be written to one of the sockets in the set of pending sockets. We present the details of our implementation of this approach is Section 3.

Problem: Bloated Socket Buffers: Jansen *et al.* observed that relays may have several thousands of TCP sockets opened at any time, and that the size of each of their send buffers are automatically tuned (monotonically increased) by the kernel in order to ensure that the connection can meet the bandwidth delay product and fully utilize the link. TCP-autotuning [19] increases throughput when few sockets are active, but was found to cause bufferbloat and increase kernel queuing time in Tor networks where hundreds or thousands of sockets may be simultaneously active.

Solution: Socket Write Limits: To reduce bufferbloat, KIST limits how much it will write to each TCP socket based on the TCP connection's current congestion window and the number of unacknowledged packets. These values are collected from the kernel using `getsockopt(2)` on level `SOL_TCP` for option `TCP_INFO`, and used to estimate the amount of data that the kernel could immediately send out into the network (i.e., it would not be throttled by TCP). KIST limits how much it will write to a socket by the minimum of this estimate and the amount of free space in each socket buffer. Finally, KIST includes a global write limit across all sockets to ensure that the amount of data written to the kernel is not more than the network interface would be able to send.

3 KIST Implementation

We now describe our implementation of KIST to support both global circuit scheduling and socket write limits. We highlight optimizations that we made to the original algorithm in order to make KIST more suitable for a production environment.

3.1 Supporting Global Circuit Scheduling

After discussing KIST with the Tor developers, they refactored the socket writing logic described in Section 2.2 into a new *socket scheduler* that manages the process of writing cells from the circuits to the output buffers and the kernel (Figures 2🅔 and 2🅕). The Tor developers also implemented a *socket scheduling policy*[2] that (i) runs the socket scheduler to write cells to the kernel immediately whenever a circuit has pending cells, and (ii) follows Tor's previous default behavior of writing as much as possible from pending circuits to writable sockets. We call this the "as much as possible" (AMAP) socket scheduling policy.

Although AMAP maintains Tor's previous functionality, it also inherits its limitations. In particular, because AMAP writes as much as possible and as often as possible, libevent essentially dictates that sockets get written in a non-configurable order and therefore circuit priority is ineffective. However, the new scheduling framework allows us to fully implement KIST: it allows for the queuing of writable sockets and for delaying the process of writing to those sockets.

3.2 Supporting Socket Write Limits

We refactored Tor socket scheduling code in order to allow for the implementation of multiple, distinct socket scheduling policies, and implemented KIST to limit the amount of data that is written to the kernel.

3.2.1 KIST Implementation

Algorithm 1 presents KIST, which we implemented in Tor `0.2.8.10` and are preparing to submit to the Tor developers for merging into a future release. When using KIST, the socket scheduler is executed on a configurable repeating period.

First, KIST performs one system call for each pending socket in order to update its cache of TCP information. In Section 5.2 we evaluate the overhead of this process. Second, KIST chooses the socket to which it will write using the *priorityPop* function, which returns the pending socket with the best priority circuit. KIST writes one cell from this circuit to Tor's outbuf and immediately flushes it to the kernel in order to maintain inter-socket

[2] Both the socket scheduler and the default policy were merged into Tor version `0.2.6.2-alpha` in December 2014.

Algorithm 1 The KIST socket scheduling policy.

$L_s \leftarrow getPendingSockets()$
for s **in** L_s **do**
    $s.updateTCPInfo()$
end for
while $len(L_s) > 0$ **do**
    $s \leftarrow priorityPop(L_s)$
    $s.circSched.flush(1)$
    $s.writeOutbufToKernel()$
    if $s.circSched.hasCells()$ **and** $s.canWrite()$ **then**
        $priorityPush(L_s, s)$ {also updates priority}
    end if
end while

priority and avoid the non-deterministic flush order that is normally imposed by libevent.[3]

KIST then uses $s.canWrite$ to check both that the socket can be written to and that the write amount has not reached the per-socket limit defined by

$$limit \leftarrow (2 \cdot cwnd \cdot mss) - (una \cdot mss) - notsent$$

where *cwnd* is size of the congestion window in packets, *una* is the number of sent but unacked packets, *mss* is the maximum segment size, and *notsent* is the number of bytes written to the kernel that have not yet been sent.[4] This slight variation on the previously proposed per-socket limit [12] ensures that the kernel can immediately send packets in response to incoming acks rather than waiting for Tor to write more data the next time that the scheduler is run. If the socket can be written to and the limit has not been reached, *priorityPush* returns the socket to the pending list with its updated priority.

3.2.2 KIST Optimizations

During our implementation and testing of KIST, we made the following observations that led us to reduce its overhead and complexity.

Ignore Idle Sockets: Jansen *et al.* [12] suggested that Tor collect information on every open socket that is connected to another Tor relay. The Tor network consists of approximately 7,500 relays [3], which serves as an upper bound on the number of sockets that may need scheduling. Our live network tests reveal a fast relay can expect to be connected to 3,000-4,000 others at any time. However, as our overhead analysis in Section 5.2 shows, our Tor relay never accumulated more than 127 *pending* sockets (those with available write-pending cells) in a 10 millisecond period. By only updating TCP informa-

[3] For performance reasons, KIST actually flushes a just-written output buffer to the kernel only when (i) the next scheduling decision would cause a write to a new socket, or (ii) no pending sockets remain.

[4] The Linux kernel provides *notsent* when `TCP_INFO` is queried as of version 4.6 (released 2016-05-15); on older kernels, it can be retrieved using `ioctl(2)` with request `SIOCOUTQNSD`.

tion on these pending sockets, we can greatly reduce the amount of time spent making system calls.

Ignore Socket Buffer Space: Jansen *et al.* [12] suggested a per-socket write limit of the minimum between free socket buffer space and TCP's congestion window. However, we found that the congestion window was the limiting factor is the vast majority of cases. We can reduce the number of system calls per socket from three to one by ignoring socket buffer space entirely. Even if the socket buffer were to run out of space, we can expect that the kernel will push back and propagate the socket's non-writable state to libevent, which will prevent Tor from attempting to write to it.

Ignore Global Write Limit: Jansen *et al.* [12] suggested that KIST should enforce a global write limit across all sockets (in addition to per-socket write limits). We did not implement this enforcement in order to reduce code complexity, since our large network simulations described in Section 4 show that a global write limit is unnecessary for preventing bufferbloat given that the per-socket limits are in place.

4 Simulation Evaluation

In this section, we describe our Tor network evaluation of KIST and show its performance impact across a variety of network conditions.

4.1 Private Tor Network

We evaluate KIST using Shadow [1, 13], a discrete-event network simulation framework. Shadow uses function interposition to intercept all necessary system calls and redirect them to their simulated counterpart, thereby emulating a Linux operating system to any applications it runs. Shadow transparently supports applications that create threads, open UDP and TCP sockets, read and write to sockets, perform blocking system calls, etc. Applications are compiled as position-independent executables and loaded into Shadow as plug-ins at run time, and then directly executed for each virtual simulation node that is configured to run it. Shadow's strong support for network-based distributed systems in general and Tor in particular make it ideal for evaluating network-wide effects of new Tor algorithms.

Shadow directly executes Tor as virtual processes that are connected through a simulated network. Although a Tor process will attempt to connect to the live, public Tor network by default, we utilize Tor's private Tor network configuration option to create a network with our own relays, clients, and servers—all hosted within the Shadow simulation framework and without direct Internet access.

Virtual Hosts: We generated a private Tor network using the methods of Jansen *et al.* [11] and public Tor metrics data from `2017-01`. Our base configuration included a total of 2,000 Tor relays, 49,800 Tor clients, and 5,000 file servers. The client behavior is as follows. Each of 300 *ShadowPerf* clients downloads a 50 KiB, 1 MiB, or 5 MiB file and pauses 60-120 seconds before repeating the download on a new circuit. This behavior mimics the *TorPerf* download pattern that is used in the public Tor network to benchmark performance over time [3], and allows us to understand the fidelity to the public Tor network. Each of 1495 *bulk* clients repeatedly download 5 MiB files without pausing, while each of the 48,005 *web* clients download 320 KiB files and pause for a time between 1 and 60 seconds (chosen uniformly at random) before downloading another file.

Internet Model: Shadow uses a connected graph to represent the Internet paths between virtual simulation hosts. Vertices in the graph correspond to Internet routers to which a host can be connected while edges correspond to paths between routers and contain latency and packet loss attributes that Shadow uses to model the path characteristics. We use the Internet graph of Jansen *et al.* [12], a complete graph that specifies latency and packet loss rates between every pair of vertices. However, we made some modifications because it did not contain accurate packet loss rates on edges. We did not find a good source of Internet packet loss rates, and so we created a model where packet loss corresponds to the latency of an edge. First, we reduced the maximum latency allowed on a single edge to 300 milliseconds to remove long-tail outliers. Second, we set packet loss rates on the edges in the complete graph according to the following linear function of the latency of the edge (in milliseconds): $packetloss \leftarrow latency/(300)(1.5\%)$. Note that constructing an updated and more accurate graph for Shadow simulation is outside the scope of this paper, but is a problem that future work should consider.

4.2 Experiments

Using the private Tor network described above, we ran Shadow experiments with both the AMAP and the KIST socket scheduling policies that were described in Section 3. For the KIST experiments, the socket scheduler was configured to run every 10 milliseconds, as previous work has shown this to provide good performance [12]. Additionally, we experimented with the following variants on the previously described base network.

Traffic load: We varied the base network to understand how network load affects KIST: we created *low load* and *high load* network variants by removing and adding 19,600 clients, respectively.

Packet loss: We varied the base Internet model to understand how packet loss rates affect KIST: we created a *no loss* model with all packet loss rates set to 0, and we created a *high loss* model with packet loss rates double that of the base model (to a maximum of 3%).

We ran 10 experiments in total: one for AMAP and one for KIST for the base network as well as each of

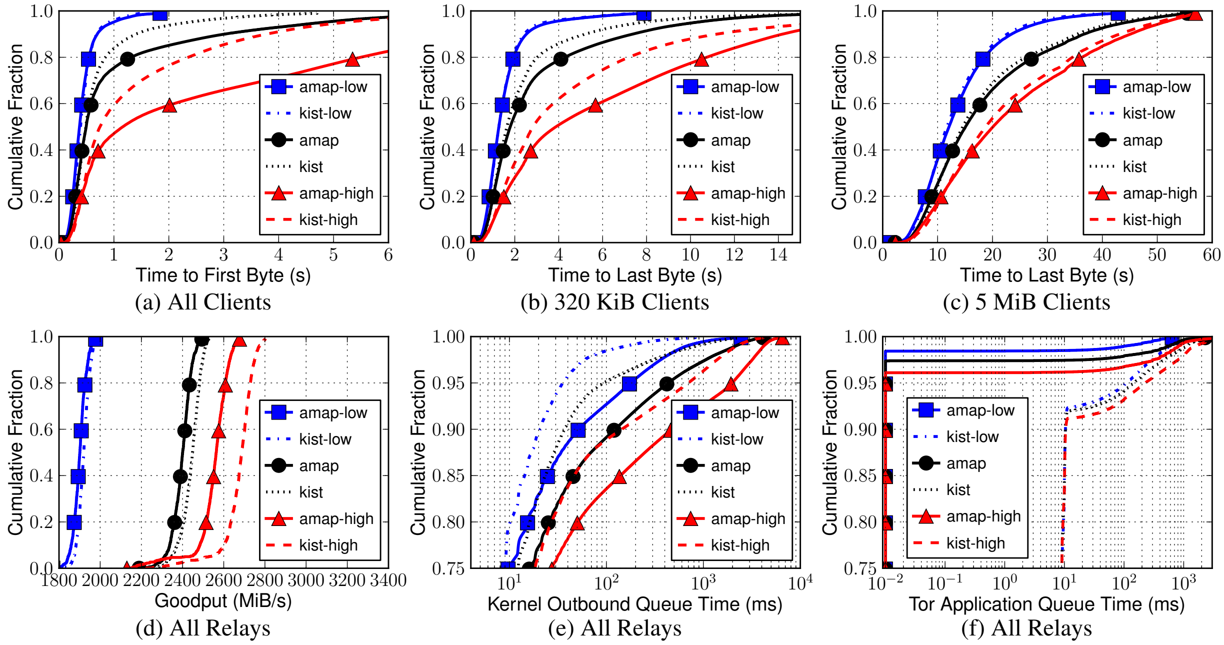


Figure 3: Client and relay performance aggregated across clients and relays for our varying traffic load models.

the four variants. Each experiment consumed between 0.5 and 1 TiB of RAM and simulated 45 minutes of full network activity in 6 to 8 days running on our hardware. We collected client download times, and we instrumented our relays to collect goodput information (using existing Tor control port mechanisms), Tor cell queuing times (using a cell tracing patch we developed), and kernel queuing times (with a Shadow patch).

4.3 Results

We evaluate and compare KIST and AMAP across a variety of different performance metrics.

Effects of Traffic Load: The performance effects of traffic load on AMAP (solid lines) and KIST (non-solid lines) are shown in Figure 3, where the line colors indicate the low, normal, and high load models.

Client performance is shown in Figures 3a-3c as the time to reach the first and last byte for all completed client downloads, across the low, regular, and high traffic load models. We make three major observations from these results. First, when there is low traffic load on the network, clients download times are generally unaffected by the choice of scheduling policy (all of the blue lines in 3a-3c showing download times under low packet loss are roughly overlapping). Second, download times increase across all scheduling policies as the load on the network increases, but the increase is greater for AMAP than for KIST (i.e., downloads with KIST finish more quickly than those with AMAP as load increases). Third, client performance when using KIST is no worse and generally much better than when using AMAP, but the improvement over AMAP diminishes as download size increases and the EWMA circuit scheduler's priority mechanisms become effective at preferring lower-throughput flows.

Relay performance is shown in Figures 3d-3f. Figure 3d shows that aggregate Tor network goodput per second is higher when using both scheduling policies as the network load increases, matching intuition. Goodput increases over AMAP when using KIST as network load increases, but the improvement that KIST provides is most significant on the highest-load model that we tested. Figure 3e shows that KIST generally reduces kernel queue time by more than it increases Tor queue time as shown in Figure 3f, suggesting that KIST is capable of reducing congestion overall rather than simply relocating it. Note that Tor queue time in Figure 3f is nearly zero for AMAP across all three load models, as Tor writes as much as possible to the kernel and tends to not queue data in the application layer. Also note that the sharp elbow at 10 milliseconds for KIST is due to the configured interval in which the scheduler is run.

Effects of Packet Loss: The performance effects of packet loss for AMAP (solid lines) and KIST (non-solid lines) are shown in Figure 4, where the line colors indicate the no, normal, and high packet loss models.

Client performance is shown in Figures 4a-4c. Recall that the general trend with the varying load models was that KIST and AMAP both reduced client performance as load increased, but the reduction when using KIST was less than when using AMAP. However, the general trend when varying packet loss is a bit different. When no packet loss is present, similar performance is achieved with both AMAP and KIST. However, as packet loss increases, AMAP tends to worsen low-

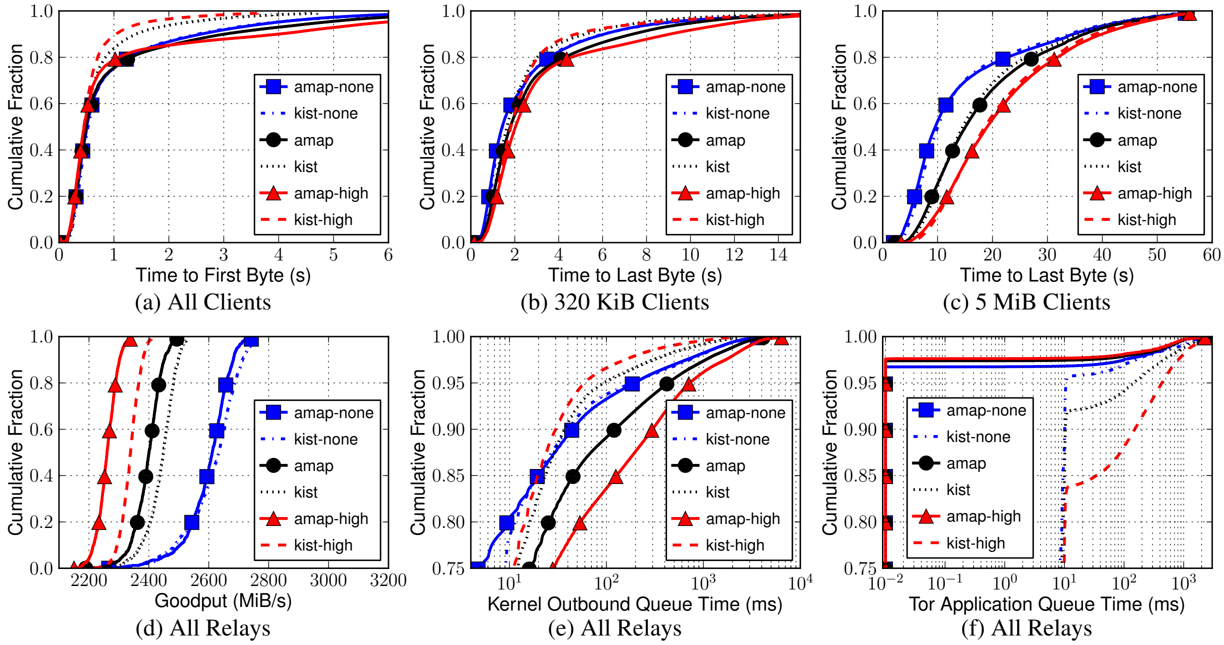


Figure 4: Client and relay performance aggregated across clients and relays for our varying packet loss models.

volume client performance while KIST tends to improve it. Figure 4a and 4b both show that KIST actually performs best with high packet loss while AMAP performs worst, while Figure 4c shows similar results as for varying load: the improvement diminishes for 5 MiB downloads since the circuit priority mechanism is operating effectively. We suspect that KIST achieves better performance for low-volume traffic at higher packet loss rates because it effectively deprioritizes high-volume circuits; the less-congested kernel can then react more quickly to low-volume traffic as Tor prioritizes its delivery to the kernel. More work is needed to verify this suspicion.

Relay performance is shown in Figures 4d-4f. Figure 4d shows that aggregate Tor network goodput decreases as packet loss increases, but it decreases less when using KIST than when using AMAP. Figure 4e shows again that KIST is able to reduce kernel queue time more as packet loss rates increase, while AMAP increases kernel queue times as packet loss rates increase. Finally, the general trends in Figure 4f are similar that of the Tor queue times under the varying load models: Tor queue time is nearly zero when using AMAP for all tested loss models, while it is 10 milliseconds or less for over 80 percent of the data when using KIST.

5 Live Network Evaluation

In this section, we evaluate KIST by running it on a live relay in the public Tor network.

5.1 Deploying KIST

The KIST scheduling decisions are all local to each relay, and function independent of the other relays in a circuit. As a result, KIST is naturally incrementally deployable. This allows us to deploy KIST on a single relay under our control in the public Tor network to further understand its real-world performance effects.

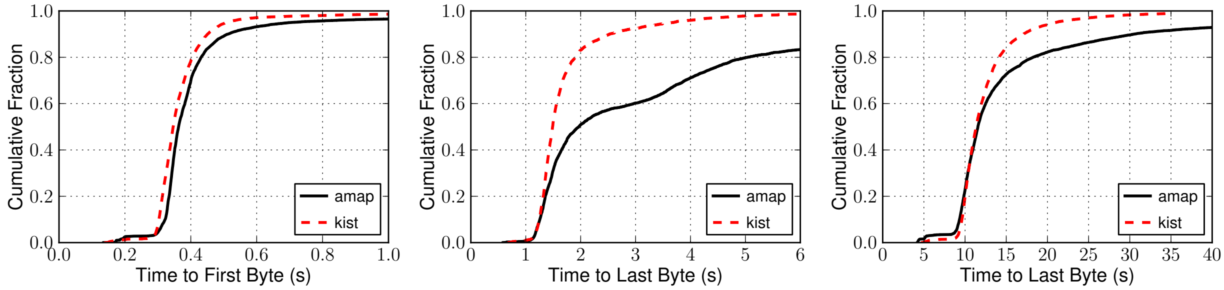
We ran a Tor exit relay[5] with the default exit policy on a bare-metal machine rented from Hurricane Electric (an Internet service provider). The machine had a 4-core/8-thread intel Xeon E3-1230 v5 CPU running at 3.40 GHz, and was connected to a unmetered access link capable of a symmetric bandwidth of 1 Gbit/s (2 Gbit/s combined transmit and receive). Several unrelated relays were co-hosted on the machine, but the average combined daily bandwidth used did not exceed 1.5 Gbit/s.

We ran our relay for several weeks before starting a 2 day experiment where we ran KIST and AMAP for one day each. During this experiment, we also ran three *web* clients that download 320 KiB files and pause an average of 60 seconds between downloads, and two *bulk* clients that download 5 MiB files and pause for 1 second between downloads. The clients choose new entry and middle relays for every circuit, but we pin our relay as the exit. As in the Shadow simulations in Section 4, we instrumented our relay to collect goodput, Tor cell queuing times, and kernel queuing times, and we instrumented our clients to collect file download times.

5.2 Results

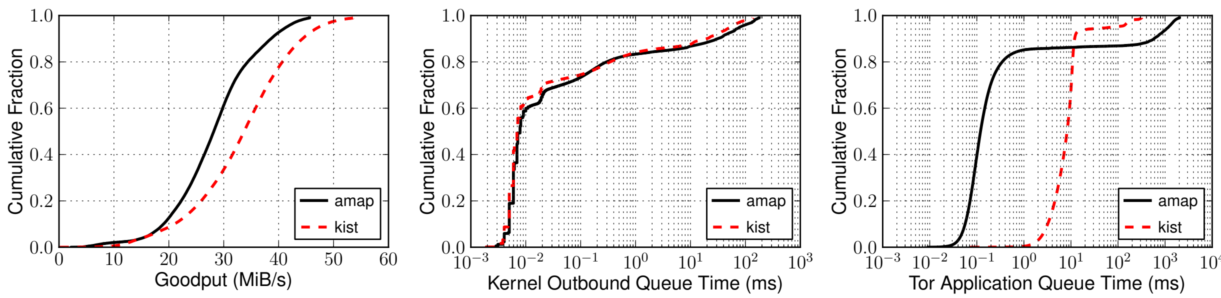
During our experiment, the web clients finished 7,770 downloads and the bulk clients finished 18,989 downloads. Figure 5 shows the distributions of download times recorded by our clients. While KIST reduced

[5] The relay fingerprint was `0xBCCB362660`.



(a) All Clients (b) 320 KiB Clients (c) 5 MiB Clients

Figure 5: Client performance aggregated across five clients downloading through the live Tor network.



(a) (b) (c)

Figure 6: Tor relay performance on our fast exit relay running in the live Tor network.

download times relative to AMAP across all metrics, the relative improvement was greater for 320 KiB files (Figure 5b) than for 5 MiB files (Figure 5c); this could indicate that circuit priority was more effective under KIST, although we note that there may be network effects outside of our control that are also influencing the results.

Figure 6 shows the performance results collected on our relay. Figure 6a shows that KIST increased goodput relative to AMAP during our observational period. Although Figure 6b shows an insignificant change in kernel outbound queue time, Figure 6c shows that KIST increased Tor application queuing time by less than 10 milliseconds (the configured scheduling interval) for over 90 percent of the sampled cells; we suspect that the relatively higher Tor queue time for the remaining sampled cells is due to the circuit scheduler effectively deprioritizing high-volume circuits. Additionally, KIST reduced the worst case application queue times from over 2,000 milliseconds to less than 400 milliseconds.

We also collected the overhead of performing the `getsockopt(2)` call to retrieve TCP information for write-pending sockets. We observed that the median number of write-pending sockets that accumulated during a 10 millisecond period was 23 (with min=1, q1=18, q3=27, and max=127), while the median amount of time to collect TCP information on all write-pending sockets was 23 microseconds (with min=1, q1=17, q3=33, and max=674). We observed a linear relationship between the amount of time required to collect TCP information on all write-pending sockets and the number of such sockets (1.08 microseconds per pending socket), independent of the total number of open sockets. Therefore, we believe that the KIST overhead, with our optimization of only collecting TCP information on pending sockets, should be tolerable to run in the main thread for even the fastest Tor relay.

6 Conclusion

In this work, we implemented KIST with a goal of deploying it into the Tor network. We evaluated its performance impact in simulation under a range of network load and packet loss conditions, and found that KIST can improve client and relay performance, particularly when a relay is under high load or high packet loss. We also ran KIST in the public Tor network, and found that KIST has an indistinguishable effect on relay throughput and kernel queuing times. We will release our implementation as open-source software so that it can be included in a future Tor release.

Lessons Learned: As with most Tor research, we found it useful to communicate with the Tor developers early and often. They are experts in developing and maintaining anonymous communication systems and their collaboration and feedback greatly improved the quality of this work. Still, we found it to be extremely time-consuming to produce a working implementation given the complexities of both the Tor software and the way that it interoperates with TCP and the kernel. We advise those interested in deploying Tor research to carefully compare the costs and benefits of creating new knowledge through additional research with those of deploying previous research proposals.

Future Work: Future work should consider creating updated data-driven models of latency and packet loss rates between relays that would be useful to Tor experimentation tools like Shadow. This could be done using direct measurement with RIPE Atlas probes or tools like Ting [7]. More work is also needed to verify our simulation findings that KIST is capable of increasingly improving performance for low-volume traffic under high load and packet loss rates in the public Tor network.

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