# FlashFlow: A Secure Speed Test for Tor

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## Abstract

The Tor network uses a measurement system to estimate its relays' forwarding capacity and to balance traffic among them. This system has been shown to be vulnerable to adversarial manipulation. Moreover, its accuracy and effectiveness in benign circumstances has never been fully quantified. We first obtain such a quantification by analyzing Tor metrics data and performing experiments on the live network. Our results show that Tor currently underestimates its true capacity by about 50% and improperly balances its traffic by 15–25%. Then, to solve the problems with security and accuracy, we present FlashFlow, a system to measure the capacity of Tor relays. Our analysis shows that FlashFlow limits a malicious relay to obtaining a capacity estimate at most 1.33 times its true capacity. Through realistic Internet experiments, we find that FlashFlow measures relay capacity with ≥89% accuracy 95% of the time. Through simulation, we find that FlashFlow can measure the entire Tor network in less than 5 hours using 3 measurers with 1 Gbit/s of bandwidth each. Finally, simulations using FlashFlow for load balancing shows that, compared to TorFlow, network weight error decreases by 86%, while the median of 50 KiB, 1 MiB, and 5 MiB transfer times decreases by 15%, 29%, and 37%, respectively. Moreover, FlashFlow yields more consistent client performance: the median rate of transfer timeouts decreases by 100%, while the standard deviation of 50 KiB, 1 MiB, and 5 MiB transfer times decreases by 55%, 61%, and 41%, respectively. We also find that the performance improvements increase relative to TorFlow as the total client-traffic load increases, demonstrating that FlashFlow is better suited to supporting network growth.

## 1 Introduction

Tor [15] is the most popular system on the Internet for anonymous communication. Tor is currently comprised of about 6,500 geographically diverse volunteer-operated proxy *relays* transferring nearly 200 Gbit/s in aggregate traffic from between 2 million [8] and 8 million [26] daily active users. Tor has seen significant growth recently, nearly doubling the amount of traffic it forwards in the last two years [8].

Tor uses a load-balancing system called TorFlow [30] to balance load from its millions of users across its thousands of relays. The goal of TorFlow is to equalize Tor performance across all clients, regardless of which relays they use. It receives bandwidth self-measurements from relays and also makes active measurements of download speeds through each relay. It then computes per-relay weights by multiplying the self-measured bandwidths by their actively measured speed relative to the average. Clients choose relays for their circuits with probabilities proportional to these weights.

Previous work has shown that TorFlow is insecure. A malicious relay can increase the fraction of traffic it can observe beyond the fraction of Tor bandwidth it provides [11, 12, 25, 36], increasing its ability to deanonymize Tor users using a traffic correlation attack [24, 28]. A main reason for its vulnerability is that it trusts relays to accurately self-report their observed capacity. Also, TorFlow's active measurements are supposed to occur concurrently with normal client traffic, but a malicious relay can detect its measurement and throttle client traffic to increase its measured speed.

In addition to its insecurity, TorFlow has not been demonstrated to be accurate even when not under attack. A relay estimates its capacity using the maximum amount of throughput it is able to sustain for any 10 second period over each of the last 5 days [14, § 2.1.1]. However, a relay that is consistently under-utilized may never produce an accurate self-estimate of its capacity, leading TorFlow to produce lower weights for that relay than it should. Moreover, the active measurements depend on client traffic and the speed of other relays randomly chosen for the same measurement circuits, potentially leading to suboptimal and variable weights. Inaccurate weights reduce client performance by improperly balancing load. Moreover, inaccurate capacity estimates make it more difficult to understand how to spend research and development effort on improving the network. For example, obtaining funding to improve Tor scalability is more challenging without understanding the current limits of the network. Improper network management also complicates relay recruitment and retention, and may dissuade the development of incentive schemes [19, 21, 27, 29].

We explore the error and inconsistency in Tor's estimated relay capacities and weights using Tor metrics data [8] and an active measurement experiment. Our analysis of 11 years of data shows that 25% of relays have a mean capacity error of 49% or greater, that total network capacity error has reached as high as 60%, and that relay capacity estimates vary by 82% or greater for 25% of relays. The analysis also shows median load balancing errors between 15% and 25% over time. Our measurement experiment on Tor further indicates that relays significantly under-estimate their own capacity, and the network capacity as a whole is underestimated by about 50%.

We present FlashFlow to solve these problems. FlashFlow is a system designed to securely, accurately, and quickly measure the capacity of relays in the Tor network. In addition to providing weights for load balancing, the capacity measurements allow Tor to accurately assess the network's resources and plan for the future.

The need for security heavily influences the design choices of FlashFlow. We cannot make use of measurement approaches that are vulnerable to manipulation, such as packet pairs [31]. Previously proposed systems attempt to measure Tor surreptitiously [9, 30] or to securely aggregate passive observations made by many relays [25, 34]. FlashFlow takes a new approach to this problem by using separate measurement teams that attempt to actively utilize the *full* capacity of relays. This approach improves security as it requires the direct demonstration of a relay's capacity rather than relying on an indirect measurement that may be falsifiable. It also yields higher accuracy, as the traffic is actively generated to determine the relay's limit, with the normal client traffic carefully reduced to limit its impact on the result without excessively reducing client performance. FlashFlow additionally aggregates results from multiple measurers in order to accurately measure the highest-bandwidth relays in Tor.

We implement FlashFlow and conduct extensive experiments in a lab setting, on the Internet, and in simulation. With our suggested parameter settings, FlashFlow limits a malicious relay to obtaining a capacity estimate of at most 1.33 times its true capacity. Through Internet experiments across a range of geographic locations, we find that FlashFlow is able to measure a target relay with a capacity ranging from 10 Mbit/s to 1 Gbit/s to within 11% of ground truth in 30 seconds 95% of the time (or within 20% of ground truth 99.8% of the time). Through simulation, we find that FlashFlow can measure the entire Tor network in less than 5 hours using 3 measurers each with 1 Gbit/s of bandwidth. Through private Tor network simulations in Shadow, we find that FlashFlow reduces network weight error by 86%. The resulting improvement in load balancing reduces transfer times for *all* tested transfer sizes: the median of 50 KiB, 1 MiB, and 5 MiB transfer times decreases by 15%, 29%, and 37%, respectively. FlashFlow also yields more *consistent* client performance: the median rate of transfer timeouts decreases by 100%, while the standard deviation of 50 KiB, 1 MiB, and 5 MiB transfer times decreases by 55%, 61%, and 41%, respectively. Finally, we find that the performance improvements increase further as the total client-traffic load increases, demonstrating that FlashFlow is better suited to supporting Tor network growth than is TorFlow.

## 2 Background

**Overview:** As of August 2019, the Tor network includes about 6,500 *relays* that forward a combined 200 Gbit/s of Tor traffic, and 9 *Directory Authorities* (DirAuths) that act as trust anchors for the distribution of network information to Tor users. When new relays join the network, they publish their public key and network address to the DirAuths, who then verify reachability and validate Tor protocol support. A voting process occurs every hour, after which the DirAuths add valid relays to a *network consensus* document signed by all authorities and distributed to all Tor clients and relays. The consensus document stores information about all available relays and is required for new clients to use Tor. New relays that appear in a consensus are not used until their performance has been measured by a majority of the 6 *Bandwidth Authorities* (BWAuths) that participate in Tor's load balancing system.

**TorFlow:** Each Bandwidth Authority runs the TorFlow [30] relay-measurement tool to measure the relative performance of relays in the Tor network over time. TorFlow conducts performance measurements of Tor relays by creating 2-hop Tor circuits through them and downloading one of a set of 13 fixed-sized files ($2^i$ KiB for $i \in \{4, \dots, 16\}$) from a known destination through each circuit. Every hour, TorFlow aggregates the latest relay measurements and produces a load-balancing *weight* for each relay.

To assist in balancing load across relays, TorFlow attempts to produce larger weights for relays that can better handle Tor traffic. To compute the weights, TorFlow relies on two data sources. First, TorFlow uses each relay's self-reported bandwidth information that is published every 18 hours in a *server descriptor*. This information includes any rate limit set by the relay (e.g., with the BandwidthRate and BandwidthBurst options [7]), as well as its *observed bandwidth*, which is the highest Tor throughput that the relay was able to sustain for any 10-second period during the last 5 days [14, §2.1.1]. From this information, TorFlow computes the relay's *advertised bandwidth* as the minimum of the observed bandwidth and any rate limit set by the relay. Second, TorFlow uses the results of its own measurements to compute for each relay a ratio of the measurement speed of the relay to the mean measurement speed of all relays in the network. Finally, TorFlow computes a weight for each relay by multiplying the computed speed ratio for that relay by its advertised bandwidth.

**Load Balancing:** The TorFlow weights are collected and reported to the Directory Authorities, added to the following network consensus, and distributed to clients. Tor clients then use the normalized weights as probabilities when selecting relays for theirs path through the Tor network in an attempt to balance user load across relays. To use Tor, a client creates a *circuit* through a sequence of three relays, over which a TCP connection can then be made to any Internet host. Communication *cells* of a fixed 514-byte length are sent through the circuit and are encrypted (or decrypted, depending on the direction) by each relay using a key exchanged with the client during circuit construction.

**Terms:** We use the term *throughput* to mean an amount of traffic that an application or a segment of the network stack (e.g., TCP) has been measured to have forwarded (i.e. received and then sent). We use the term *capacity* to mean the maximum throughput that an application or network segment can handle. Thus a *Tor throughput* is an amount of traffic that a Tor process has been measured to have forwarded, potentially as an estimate of *Tor capacity*. Tor throughput includes cell payloads and headers but excludes TCP, IP, and other network packet headers. Finally, *Tor ground truth* is an estimate of Tor capacity experimentally determined by sending load from increasing numbers of simulated clients and measuring them at the relay. Tor ground truth measurements are accurate but expensive and require trust in the relay.

# 3 TorFlow Analysis

A primary goal of Tor's load balancing system is to drive more user traffic to Tor relays that can better support it. Fundamentally, Tor attempts to spread user load among relays according to two relay characteristics: (i) relay capacity, i.e., the maximum rate at which a relay can forward Tor traffic; and (ii) relay performance, i.e., the current speed of fixed-size download. As explained in § 2, TorFlow uses relays' advertised bandwidths as an estimate of relay capacity, and its own client measurements to estimate relay performance. Because TorFlow uses relay capacities as the basis for the load-balancing weights it produces, accurate relay capacity estimates are essential to load balancing and, ultimately, Tor network performance and scalability.

A relay's capacity estimate is derived from a heuristic measure of unknown accuracy, i.e., its observed bandwidth (see § 2). The observed bandwidth is likely inaccurate in many realistic cases: (i) a *new* relay will not have forwarded any traffic and thus will be estimated to have a low capacity regardless of its available resources; (ii) a relay that clients use *inconsistently* may not sustain a high throughput long enough to result in an accurate capacity estimate; (iii) a relay that clients *underutilize* will underestimate its capacity; and (iv) a relay with co-resident processes that consume bandwidth *inconsistently* may overestimate its capacity.

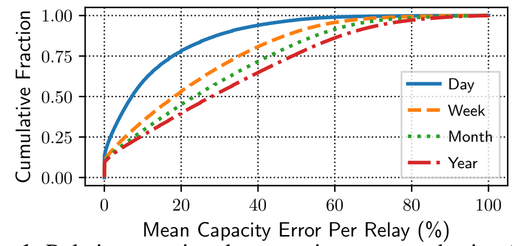



**Figure 1:** Relative error in relay capacity, computed using 11 years of archived Tor metrics data [8].

To better understand the accuracy of Tor's capacity-estimation heuristic and its effect on load balancing, we analyze publicly available Tor metrics data over time. Relays' capacity estimates are published in their server descriptors [14, § 2.1.1], and load-balancing weights are published in network consensus files [6, § 3.4.1]. The Tor Project has collected these documents for over a decade, and it publishes monthly archives [8]. We use 11 years of such data from the period 2008-08-01 to 2019-07-31, and we analyze the error in both capacity estimation and load balancing.

## 3.1 Capacity Estimation Analysis

We compute the inaccuracy of relay capacity estimates across relays and over time. In our analysis, we suppose that a relay's true capacity does not often change (it usually runs on the same machine with the same network interface card and access link) and that a relay's observed bandwidth is not higher than its true capacity (a relay's capacity is not usually limited by co-resident processes).

**Relay Capacity Accuracy:** We observe that advertised bandwidths exhibit high variance over time, which suggests that they often underestimate true capacity (see Appendix A). To quantify this error, we use a relay's maximum advertised bandwidth over a given time period as a proxy for its true capacity. Comparing advertised bandwidths to this maximum should yield a conservative error estimate, as the maximum should only be lower than the true capacity, assuming the true capacity does not vary during the given period.

Let $A(r,t)$ be the advertised bandwidth of relay $r$ at time $t$, and let $A(r,t,p)$ be the multiset of advertised bandwidths published during the period of length $p$ preceding time $t$. Varying the length of time $p$ allows us to examine error over different timescales. We thus estimate the true capacity of relay $r$ at time $t$ using the maximum bandwidth during the period of some length $p$ preceding $t$:

$$C(r,t,p) = \max\left(A(r,t,p)\right). \quad (1)$$

We can then assess the *relay capacity error* for relay $r$ at time $t$ as the fraction by which its advertised bandwidth underestimates the maximum observed in the previous $p$ time:

$$\mathrm{RCE}(r,t,p) = 1 - A(r,t)/C(r,t,p). \quad (2)$$

We summarize these errors by computing the mean of $\mathrm{RCE}(r,t,p)$ over the times $t$ on the hours between 2009-08-01 and 2019-07-31. We plot the distribution of these means over all relays $r$ in Figure 1 for various values of $p$.

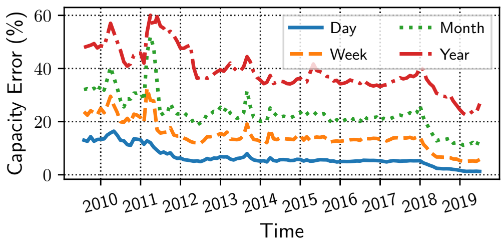



**Figure 2:** Network capacity error over time, computed using 11 years of archived Tor metrics data [8].

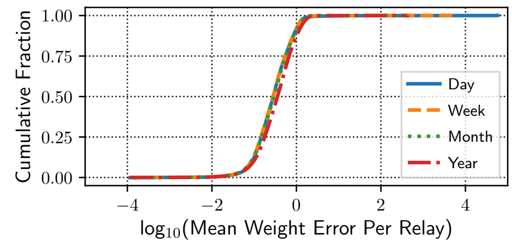



**Figure 3:** Relative error in relay weights, computed using 11 years of archived Tor metrics data [8].

From the results in Figure 1, we observe that larger errors are estimated when the true capacities are based on longer time periods: the median of the mean capacity error is 28% when true capacities are computed using 1 year of reports, compared to 7% when they are computed using only 1 day of reports. A plausible explanation for this observation is that relays are typically underutilized and experience random load fluctuations, and so the longer a relay is observed the more likely it is to receive traffic at or close to its true capacity. We also find that over 85% of relays have non-zero capacity error, and for 25% of relays the capacity error is 18% or greater for $p = 1$ day and 49% or greater for $p = 1$ year. Overall, our results indicate significant underestimation of true capacities.

**Network Capacity Accuracy:** Although Figure 1 shows non-trivial error in the *relay* advertised bandwidths, it does not necessarily indicate that the *network* suffers from inaccuracy as a whole. For example, it could be the case that relays with highly erroneous advertised bandwidths are slow relays that do not carry much user traffic. Therefore, we also explore a notion of network accuracy. We compute the *network capacity error* at time $t$ by summing the advertised bandwidths and true capacities from all relays and then calculating the fraction of total network underestimation:

$$\text{NCE}(t,p) = 1 - \sum_r A(r,t,p) / \sum_r C(r,t,p). \tag{3}$$

The network capacity error gives us an understanding of the total fraction of Tor's capacity that is being underestimated, as opposed to the fraction of relays with underestimation.

We show Tor's network capacity errors over time in Figure 2. In the median hour between 2009-08-01 and 2019-07-31, we find a network capacity underestimate of 5% when using the preceding day to determine true capacities, 14% when using the preceding week, 22% when using the preceding month, and 36% when using the preceding year. As with relay capacity errors, we see larger errors when we determine the true capacity based on longer periods. The largest network capacity error we discovered was 60% (for $p = 1$ year). These results provide evidence that Tor significantly and consistently underestimates its total capacity. We discuss additional conclusions in § 3.3.

## 3.2 Load Balancing Analysis

Our previous results quantify the inaccuracy present in the relays' advertised bandwidths. A main reason such inaccuracy is a problem is that it affects the consensus weights used by clients to balance load across relays. We analyze these consensus weights over time to better understand the accuracy in the load balancing system.

**Relay Weight Accuracy:** The probability that a relay is selected in a circuit is roughly its normalized consensus weight, that is, its fraction of the total weight assigned to all relays. Let $W(r,t)$ represent this value for relay $r$ at time $t$, and let $W(r,t,p)$ be the multiset of these values over the consensuses during the period of length $p$ preceding time $t$. Ideally, a relay's normalized consensus weight would equal its normalized capacity, that is, its fraction of the total capacity. Let $\overline{C}(r,t,p)$ be the normalized capacity of relay $r$ at time $t$:

$$\overline{C}(r,t,p) = C(r,t,p) / \sum_s C(s,t,p). \tag{4}$$

At any time $t$, we can consider any deviation of the normalized consensus weight $W(r,t)$ from the normalized capacity $\overline{C}(r,t,p)$ as error. We can then quantify this *relay weight error* by computing the ratio of these values:

$$\text{RWE}(r,t,p) = W(r,t) / \overline{C}(r,t,p). \tag{5}$$

We then collapse the results to a single value per relay by computing the mean over all $t$ starting from $t$ = 2009-08-01. Notice that it is possible that the normalized consensus weight is less than the normalized capacity, in which case $\text{RWE}(r,t,p) \in [0,1)$, and that the normalized consensus weight is greater than the normalized capacity, in which case $\text{RWE}(r,t,p) > 1$. Therefore, to better visualize the results, we plot in Figure 3 the distribution of the per-relay means of $\text{RWE}(r,t,p)$ (over all $t$) by taking the $log_{10}$ of the means. As a result, x-axis values less than 0 indicate that relays are under-weighted compared to their capacity, and x-axis values greater than 0 indicate that relays are over-weighted compared to their capacity (by a factor of 10 for each unit). The results show that more than 85% of relays are under-weighted compared to what we would expect based on their capacities, while few relays (at $x = 0$) are ideally weighted. Since consensus weight is zero-sum, it must be the case that the disproportionately small number of relays that are over-weighted account for a disproportionately large amount of total user load; we account for this in the following metric.

**Network Weight Accuracy:** To get a better sense of how weight errors affect the network overall rather than individual relays, we compute the *network weight error* as the *total*

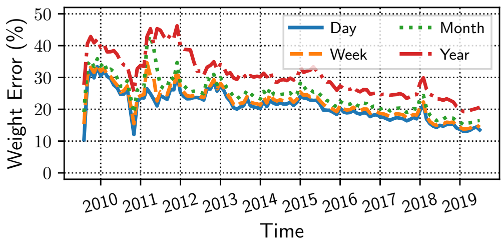


**Figure 4:** Network weight error over time, computed using 11 years of archived Tor metrics data [8].

*variation distance* between the normalized consensus weight and the normalized capacity:

$$\text{NWE}(t,p) = \frac{1}{2}\sum_{r} \mid W(r,t) - \overline{C}(r,t,p) \mid . \qquad (6)$$

This better represents error in Tor's load balancing system overall, since subtracting the normalized values (rather than dividing them as we did in Equation 5) means that relays will contribute to the network error proportional to the amount of traffic they carry. Figure 4 shows the network weight error $\text{NWE}(t,p)$ over time starting from $t$ = 2009-08-01 for various values of $p$. We again observe that error increases as our capacity estimates are based on data from longer periods. However, the difference in error over greater values of $p$ is much less pronounced: the network weight error is 21%, 22%, 24%, and 30% in the medians when using normalized capacities from the preceding day, week, month, and year, respectively. Our results over the latest year of data (2019) show a 15-25% error in load balancing weights, indicating that Tor will benefit from improvements to their load balancing system.

## 3.3 Conclusions and Observations

Our analysis shows consistent error in both network capacity and network weights over time. We make two observations from our results. First, we observe that we get a significantly higher estimate of true capacity when aggregating more advertised bandwidths into the estimate, and we generally find significant under-weighting of relays relative to their capacity. Second, we observe that both capacity and weight error has decreased in recent years (2018–2019) compared to early years (2010–2011). We hypothesize that these observations result from the under-utilization of relays: a relay that is not fully utilized will report an advertised bandwidth that is below its true capacity. We suspect that the error has decreased in more recent years because Tor's increase in relay bandwidth resources has outpaced its increase in user load, and therefore even after aggregating advertised bandwidths over a year, our estimate of true capacity is still an under-estimate (leading us to compute a lower error). We further explore this hypothesis through a Tor network measurement experiment.

## 3.4 Relay Speed Test Experiment

To test our hypothesis that advertised bandwidths reported by relays under-estimate their true capacity, we designed a relay speed test experiment in which we flood each Tor relay with traffic for 20 seconds. The additional traffic that we transfer through the relays will cause them to produce better estimates of their true capacities, which they will then report in their server descriptors (see § 2).

**Setup:** We added 487 lines of code to Tor v0.3.5.7 to support a new `SPEEDTEST` cell that, when sent from a client to a supporting relay, would simply be forwarded back to the client on the same circuit. We also added client controller commands to start and stop a speed test with a particular target relay and to monitor bandwidth information during each test. We created 10 measurement "teams" that each consisted of a client and a relay running our modified Tor, and we ran a master python script that would keep track of the relays available in the network consensus over time. The master script iterated through the online relays one at a time, directing the speed test client in each team to create a circuit through the target relay to the speed test relay in that team. Once all teams' circuits were built, the speed test clients and relays sent and forwarded `SPEEDTEST` cells as fast as possible for 20 seconds, taking care not to overflow circuit queue length limits. This resulted in 20 new bidirectional, high volume sockets on each target relay, who forwarded the traffic as they would on any other circuit. We ran all speed test clients and relays on the same dedicated machine with 32 GiB of RAM, 8 CPU cores, and a 1 Gbit/s network link.

**Ethics:** We designed our experiment to minimize Tor network relay overhead. We submitted our experimental design and plans to the Tor Research Safety Board[1] for feedback. We received encouraging feedback and a "no objections" decision. We also explained our plans to the Tor community through a post to the public *tor-relays* mailing list. We gave instructions on how to opt out and allowed one week to collect feedback. Finally, we served a web page containing a link to the mailing list post on the IP addresses used in the experiment.

**Results:** Our speed test experiment ran for just over 2 days (51 hours) starting on 2019-08-06, as shown in the shaded region in Figure 5. During this time we successfully measured 4,867 relays and we observed timeouts for 2,132 relays. We plot in Figure 5 the estimated capacity of the network, i.e., the sum of advertised bandwidths for all online relays over time. We find that the estimated network capacity increases by about 200 Gbit/s (about 50%) after our speed tests push relays into reporting higher observed bandwidths, and that 10% of relays reported a change in observed bandwidth of 140 Mbit/s or more. Note that the delay in the increase and decrease in capacity relative to our experiment is caused by (i) the 18 hour server descriptor publishing interval, and (ii) the observed bandwidth algorithm which stores history for each of the last 5 days. We also plot in Figure 5 the network weight error as defined in Equation 6, which represents the overall effect on load balancing. We find that weight error increased by

[1] https://research.torproject.org/safetyboard

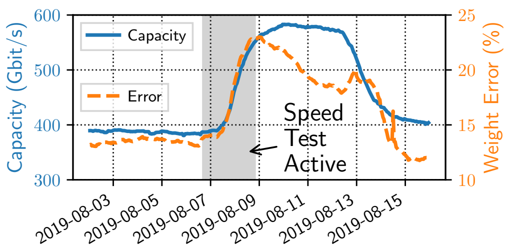



**Figure 5:** Our relay speed test discovered ≈200 Gbit/s of excess capacity (≈50%), and the network weight error (Equation 6) increased by between 5% and 10% due to more accurate capacity estimates.

between 5% and 10% as a result of more accurate capacity estimates, to a maximum of 23% during the speed test. Then, we observe a decrease in weight error immediately following our experiment, which we believe is a result of TorFlow using the new information to correct consensus weights. From these results, we conclude that Tor significantly under-estimates its available network capacity and that better estimates of capacity would reduce error in load balancing.

# 4 FlashFlow Design

We now present the design for FlashFlow, a system to measure the capacity of Tor relays. The key technique behind FlashFlow is to actively measure the full capacity of Tor relays using multiple measurement hosts. This approach improves security over prior approaches, as relays must demonstrate their true capacity, a process that cannot be faked. It also improves accuracy, as the measurement does not depend on background traffic or on other relays.

**Setup:** FlashFlow uses a *measurement team* to perform relay capacity measurements. The measurement team consists of a set of *measurers* running on hosts whose resources are dedicated to the measurement process. The measurers will cooperatively measure relays, and so the primary requirement for measurers is that they collectively have sufficient network capacity to measure all Tor relays. A team is considered to have sufficient capacity if the sum of capacities over all measurers is at least some constant factor $f$ (see § 6) times the highest Tor-relaying capacity among relays. FlashFlow is designed to achieve accurate measurement given sufficient network capacity, regardless of network latency.

The measurement team is coordinated by a BWAuth, who determines the measurement *schedule* and aggregates the results. A measurement schedule is created for each measurement *period*, which divides time into constant-length intervals. Multiple BWAuths, each with its own measurement team, independently run FlashFlow. Each BWAuth separately measures each relay during a period.

**Trust and Diversity:** As in Tor currently, each DirAuth chooses to trust some BWAuth, and the DirAuths place the median of their measurements in the consensus. Thus the trust assumption in FlashFlow is that a majority of DirAuths trust BWAuths (and their associated teams) that are honest. In the simple case that each DirAuth trusts a different BWAuth, FlashFlow requires an honest majority among the BWAuths and their teams. Moreover, FlashFlow will be more accurate if there is a diversity of network locations across measurement teams that reflects the diversity of Tor clients and relays. Such diversity will mitigate unrepresentative measurements resulting from unusually high or low network capacity between a relay and a measurement team (e.g., due to existing in the same data center).

## 4.1 Performing a Measurement

A BWAuth initiates a single measurement by creating an authenticated connection to each measurer and to the target relay. Authentication is performed using the public key of the BWAuth, which we assume is distributed in the Tor network consensus. The BWAuth sends the target the public keys of each measurer involved in the measurement. While connected, the measurers accept instructions from the BWAuth, and the relay accepts authenticated measurement connections from the measurers indicated by the BWAuth. The relay will only accept connections from a given BWAuth and its team once per measurement period.

The BWAuth will divide the total resources needed for the measurement across its $m$ measurers $M_1, \ldots, M_m$. The BWAuth allocates a quantity $a_i$ of the measurement capacity of $M_i$ to the measurement (see § 4.2 for choosing $a_i$), where $a_i = 0$ is possible and indicates that $M_i$ does not participate in the measurement. For each $M_i$, a modified Tor process is started on each CPU core without an existing measurement process (and always at least one). The measurement-traffic rate of the $k_i$ processes thus started is limited by setting the BandwidthRate parameter of each modified Tor process on the measurer to $a_i/k_i$. A constant total number of TCP sockets $s$ is used across all measurers (see Appendix E.1 for setting $s$), and each $M_i$ uses an even share $s/m$ of them, with each measuring process at $M_i$ using $s/(mk_i)$ of the sockets.

Each measuring process creates one TLS connection with the target relay for each of its allocated sockets. Over each such connection, a special measurement circuit is constructed using a new type of circuit-creation cell. A key exchange is performed, but the circuit will not be extended further. All cells received on the circuit by the target relay will be decrypted and then returned to the measurer. The target relay schedules cells on measurement circuits using a separate cell scheduler to ensure high throughput even with fewer sockets than typical for a Tor relay (the existing scheduler [22] is designed for priority scheduling across many sockets [17]). Moreover, the target relay enforces a maximum ratio $r$ between cells sent by the normal scheduler and those overall, and it attempts to send as much normal traffic subject to this maximum. This design provides an accurate measurement while ensuring that normal traffic continues to be relayed.

A relay is measured by a BWAuth during a measurement *slot*. During this time, each measuring process sends measurement cells filled with random bytes over the measurement circuit. The process sends such cells as fast as possible. The target relay decrypts those cells using the circuit key, and then returns them on the circuit. Note that both the measurer and the target perform TLS encryption and decryption, but the target alone performs Tor's cell decryption. This design minimizes the computational load of the measurer while replicating the cryptographic operations that the target would perform on normal traffic, which is needed to get an accurate estimate of its forwarding capacity. To ensure that the target is correctly decrypting and forwarding cells, the measurer records the contents of each cell sent with probability $p$ (e.g., $p = 10^{-5}$) and checks that the returned content of such cells is correct, reporting failure from the measurement if not.

A measurement slot lasts a constant number of seconds $t$ (see § 6). The BWAuth can end the measurement in this slot early due to a failure reported by a measurer. During the measurement slot, the BWAuth receives from the $i$th measuring process the number of measurement bytes $x_j^i$ that were relayed by the target to the process in the $j$th second. The BWAuth also receives from the target the number of normal traffic bytes $y_j$ that the target relayed in the $j$th second. At the end of the measurement, the BWAuth computes per-second sums of measurement traffic: $x_j = \sum_{i=1}^{m} x_j^i$. It limits the per-second normal traffic to the largest value that is consistent with the measurement traffic and the traffic ratio $r$: $\bar{y}_j = \min(y_j, x_j r/(1-r))$. The BWAuth computes a per-second estimate $z_j = x_j + \bar{y}_j$ of total bytes relayed by the target, and then it sets its capacity estimate to the median: $z = \text{median}(z_1, \ldots, z_t)$. Incorporating the normal traffic results in better capacity estimates, and enforcing the expected ratio limits how much a malicious relay can increase its capacity estimate by reporting more normal traffic than it actually relayed.

## 4.2 Measuring a Relay

Measuring a relay potentially involves a sequence of measurements because the measurer capacity required for an accurate measurement is unknown. Instead of using the maximum amount of measurer capacity for each relay, we instead use informed guesses about relays' capacities and allocate only the measurer capacity needed for those guesses. If the measurement indicates that the allocated capacity was sufficient for a given target, then we conclude the measurement process. Otherwise, we perform another measurement of the target with a higher guess and more measurer capacity. This process reduces the total amount of measurer capacity used to measure the entire network.

**Measuring Measurers:** To allocate measurer capacity, we first need to estimate the network forwarding capacity of the measurers. Measuring measurers is easier than measuring relays because (i) we only need a lower bound on the measurement capacity, as an underestimate will only affect the speed of the measurement process and not its accuracy; and (ii) we only need to measure the speed at which network traffic can be simultaneously sent and received, as the measurer doesn't relay bytes through Tor. Therefore, to estimate the network forwarding capacity of a measurer, the BWAuth instructs it to use iPerf [2] to exchange bidirectional traffic with each other measurer on the team concurrently. This measurement uses UDP to eliminate the effects of TCP congestion control that are unlikely to affect the measurement of all relays. This measurement need only be performed when a new measurer is added to the team or when the BWAuth expects the capacity of a measurer to have changed. A 60-second measurement is performed, and the capacity estimate is the median of the per-second speeds reported by iPerf.

**Measuring Old Relays:** When measuring an *old* relay, that is, one that has an existing capacity estimate $z_0$, we simply use $z_0$ as a guess for its current capacity. The BWAuth needs to allocate $f \cdot z_0$ total capacity across the measurers, where $f$ is an excess allocation factor. Let $c_i$ denote the network capacity of measurer $M_i$. The BWAuth can allocate to this measurement any amount $a_i$ of the capacity of $M_i$ subject to $0 \leq a_i \leq c_i$ and $\sum_i a_i = f \cdot z_0$. We greedily allocate capacity by repeatedly assigning the measurer with the most residual capacity to use all its remaining capacity or as much as is needed to reach $f \cdot z_0$.

The allocation factor $f$ is defined so that the measurement has a high probability of being accurate and conclusive. It depends on a multiple $m$ that is just large enough so that, for error parameters $\varepsilon_1, \varepsilon_2 \geq 0$, if a relay with true capacity $x$ is measured using at least $mx$ measurer capacity, then the capacity estimate $z$ is almost certainly greater than $(1-\varepsilon_1)x$ and less than $(1+\varepsilon_2)x$. The value for $m$ is determined experimentally (see Appendix E.2). In addition to $m$, $f$ includes a factor $(1+\varepsilon_2)/(1-\varepsilon_1)$ to ensure that $z$ cannot result from values $x' > x$ for which the measurement errors may be larger. The excess allocation factor is thus $f = m(1+\varepsilon_2)/(1-\varepsilon_1)$.

Using the capacity allocations, the team performs a measurement and obtains a capacity value $z$. This value is taken as the new estimate if it is small enough relative to the total measuring capacity that it could only result from a true relay capacity close to $z$. Specifically, $z$ is the new capacity estimate if $z < \sum_i a_i(1-\varepsilon_1)/m$. When this is true, the true relay capacity $x$ must be greater than $z/(1+\varepsilon_2)$ and less than $z/(1-\varepsilon_1)$, which implies that the estimate is accurate, i.e., that $z \in ((1-\varepsilon_1)x, (1+\varepsilon_2)x)$. If the capacity estimate $z$ is not sufficiently small, then the relay must be measured again using a higher total measurer capacity. In this case, we set $z_0 = \max(z, 2z_0)$, which ensures the allocated capacity will at least double, and we repeat the measurement with the updated capacity estimate $z_0$.

Observe that if the original estimate $z_0$ is the true capacity, then the measurement process will almost certainly conclude after one measurement. This is true because the measuring capacity was chosen to be large enough that $z < (1+\varepsilon_2)z_0$

with high probability, and when that is true the condition to use the $z$ as the new capacity estimate is satisfied:

$$z < z_0(1+\varepsilon_2) = z_0 f(1-\varepsilon_1)/m = \sum_i a_i(1-\varepsilon_1)/m.$$

**Measuring New Relays:** When measuring a *new* relay (i.e., one without a capacity estimate), we initially guess the capacity based on the capacity distribution of existing relays. New relays either have never been seen before or were last measured so long ago (e.g., a month) that their capacity measurements are no longer considered reliable estimates. For such relays, we use as a capacity estimate $z_0$ the 75th percentile measured capacity among Tor relays over the past month. When this value is sufficiently smaller than the maximum capacity measurable, this allows us to devote less measurer capacity to the measurement. We then expect that one measurement will be sufficient for 75% of new relays. Given this estimate, the measurement proceeds the same as with old relays, where again if the resulting measurement $z$ is too high relative to the allocated capacity, the relay is scheduled for another measurement with an updated estimate $z_0 = \max(z, 2z_0)$.

### 4.3 Measuring the Network

To measure all relays in the network, the BWAuths periodically determine the measurement schedule. The schedule determines when and by whom a relay should be measured. We assume that the BWAuths have sufficiently synchronized clocks to facilitate coordinating their schedules. A measurement schedule is created for each measurement period, the length $p$ of which determines how often a relay is measured. We use a measurement period of $p = 24$ hours.

To help avoid active denial-of-service attacks on targeted relays, the measurement schedule is randomized and known only to the BWAuths. Before the next measurement period starts, the BWAuths collectively generate a random seed (e.g., using Tor's secure-randomness protocol [4]). Each BWAuth can then locally determine the shared schedule using pseudorandom bits extracted from that seed. The algorithm to create the schedule considers each measurement period to be divided into a sequence of $t$-second measurement slots. For each old relay, slots for each BWAuth to measure it are selected uniformly at random without replacement from all slots in the period that have sufficient unallocated measurement capacity to accommodate the measurement. When a new relay appears, it is measured separately by each BWAuth in the first slots with sufficient unallocated capacity. Note that this design ensures that old relays will continue to be measured, with new relays given secondary priority in the order they arrive.

## 5 Security Analysis

**Properties:** FlashFlow is designed to be secure against an adversary that attempts to cause incorrect measurements. For the specific application of load balancing, we are particularly focused on preventing malicious relays from obtaining incorrectly large capacity estimates and honest relays from obtaining incorrectly small estimates. The threat model includes an adversary that runs malicious relays, malicious clients, some malicious BWAuths, and some malicious DirAuths. Honest BWAuths are assumed to use honest measurement teams. We require that a majority of the DirAuths trusts honest BWAuths.

The FlashFlow design requires a target relay to demonstrate its capacity in a way that cannot be falsified. Thus, rather than depending on self-reports (as TorFlow does fundamentally), FlashFlow has measurers actually send and receive the same cells as normal Tor clients would. Moreover, the sent cell contents are randomly generated and the received contents checked at random to ensure that the target is properly receiving, decrypting, and returning the cells during the measurement. A relay that forges responses (e.g., to skip decryption or to send early before receiving) is detected with overwhelming probability when a response cell is checked due to the random contents, and a response cell is checked with probability $p$. As a result, a malicious relay that forges $k$ responses has approximately a $(1-p)^{-k}$ chance of evading detection.

Relays are trusted to some extent to report the normal client traffic that is forwarded during a measurement. However, that client traffic is supposed to be limited to most a fraction $r$ of the total traffic, and during aggregation the BWAuth limits the reported normal traffic to be at most $r$ times the total. An honest relay will enforce the ratio, and so the aggregated measurement accurately takes into account both types of traffic. A malicious relay could send no normal traffic but report the full amount, and it could thereby inflate its capacity estimate by a factor $1/(1-r)$ above the truth.

Several features also prevent a relay from providing high capacity only while it is being measured. Measurement by any given BWAuth is performed at a randomly selected slot in a measurement period, and the randomness is known only to the BWAuths. Furthermore, the relay is measured by multiple BWAuths at separate random times, and the median of the estimates is used. For an adversary that does not control a BWAuth, an attempt to provide high capacity only during a fraction $q < 1/2$ of measurement slots will fail with probability at least 0.5. More accurately, with $n$ BWAuths the probability is $\sum_{k=n/2}^{n} Pr[B(n, 1-q) = k]$, with $B(n, p)$ binomially distributed. Relays are notified of a measurement at its beginning, but due to the shortness of the measurement slot (e.g. $t = 30$ seconds), a malicious relay has little time to adjust its capacity dynamically. The frequency with which relays are measured also forces malicious relays to be able to consistently support their measured capacities. A relay is measured once every period, and so even after a relay has been measured by a majority of BWAuths (which is expected to take a majority of the period), it can only reduce its capacity until the next period. The efficiency of FlashFlow allows the measurement period to be relatively short (e.g. every 24 hours) and thus gives little time for a malicious relay to act at a reduced capacity.

Another security benefit of a randomized measurement schedule is that it limits the opportunity for malicious clients to perform a targeted denial-of-service attack. An adversary may try to do this in order to reduce the measured capacity of certain honest relays, which would cause Tor's load balancing to shift traffic away from them. However, assuming the adversary controls no BWAuth, the adversary cannot predict when an honest relay will be measured and must perform any denial-of-service attack during most of the measurement slots in order to expect to affect the median measurement.

Finally, we observe that it is difficult for an adversary to prevent relays from being measured by flooding the network with new relays (i.e., a Sybil attack). Old relays are guaranteed to be measured during a measurement period because they are scheduled first. New relays are given second priority, and moreover they are served on a first-come, first-served basis, and so benign new relays are eventually measured.

**Limitations:** In some cases malicious relays may be able to cause FlashFlow to obtain larger capacity estimates than the relays could sustain in Tor. We argue that these limitations are shared by Tor's existing system, TorFlow, and that FlashFlow's security and accuracy advantages make it a significant improvement. Moreover, we suggest ways to improve FlashFlow in the future to mitigate these issues.

One limitation is that an adversary that has access to multiple IP addresses on the same machine can surreptitiously run multiple relays on the machine simultaneously. Tor only accepts two relays at the same IP address (a restriction that was instituted as a defense against falsely obtaining a large total bandwidth weight [10]). FlashFlow is likely to measure multiple relays on the same machine at separate times, and so each relay would obtain a capacity estimate that is the capacity of the shared machine. Tor considers this a Sybil attack, and it currently requests that each relay operator identifies all relays that they run with the MyFamily option [7]. Moreover, Tor has made use of systems designed to detect Sybils on its network [38]. Pairs of MyFamily relays (or suspected Sybils) can be measured simultaneously with FlashFlow to determine if they share the same Tor capacity, and then the measured capacity averaged over the members of a connected set. The current TorFlow system shares this issue, as the speed measurements are performed at different times, and an adversary can detect when one of its relays is being measured and reserve all capacity for the measurement circuit [25, 36].

Another limitation is that FlashFlow measurements are so short that they might measure the *burst* speed of a host rather than its sustainable Tor capacity. For some ISPs and hosting providers, higher burst capacities are supported than are consistently achievable. This can be true as a matter of practice, as a network shared by many hosts may occasionally be underutilized, or as a matter of policy, as providers may institute price-based limits on the speed of network traffic from a host. In the former case, if the burst speed is due to variable congestion of shared resources, then we expect the median of the separate and randomly scheduled measurements by different BWAuths to produce good estimates of average performance. In the latter case, if such limits are applied faster than half the length of our measurement slots (e.g., in less than 15 seconds), then FlashFlow should obtain a sustainable capacity estimate. Moreover, we again observe that this issue currently affects TorFlow, which performs relatively short downloads of files (none larger than 64 MiB).

**Table 1:** Summary of the hosts used in Internet experiments

| | US-SW | US-NW | US-E | IN | NL |
|---|---|---|---|---|---|
| **Virtual** | No | Yes | No | Yes | Yes |
| **Network Type*** | D.C. | D.C. | Res. | D.C. | D.C. |
| **BW (claimed) (Gbit/s)** | 1000 | 1000 | 1000 | N/A | N/A |
| **BW (measured) (Gbit/s)** | 954 | 946 | 941 | 1076 | 1611 |
| **RTT to US-SW (ms)** | 0 | 40 | 62 | 210 | 137 |
| **CPU cores** | 8 | 8 | 12 | 2 | 2 |
| **RAM (GiB)** | 32 | 4 | 32 | 4 | 4 |

* Network type is datacenter (D.C.) or residential (Res.)

We further note that FlashFlow is designed to measure Tor capacity and not to detect if client traffic is actually relayed. A malicious relay can send little to no real client traffic while obtaining accurate capacity estimates from FlashFlow by only sending traffic on measurement circuits. This is an additional limitation shared with TorFlow, in which the measurement circuits are easily detected [36] and thus weights can be obtained while denying all traffic except not used for measurement [25]. Such behavior seems highly observable, however, and so we leave detecting such misbehavior as a future enhancement.

## 6 Network Experiments

We measure and evaluate FlashFlow's performance and accuracy with a set of network experiments.

### 6.1 Preliminary Setup and Analysis

**Internet Vantage Points:** To perform realistic measurements on the Internet, we obtain hosts from a set of geographically diverse network locations. Table 1 summarizes the characteristics of our hosts located in Fremont, CA (US-SW), Santa Rosa, CA (US-NW), Washington, DC (US-E), Bangalore, India (IN), and Amsterdam, Netherlands (NL).

Because network bandwidth is an important factor that will affect our experiments, and because the supported bandwidth was not advertised for all hosts, we empirically estimate it using iPerf [2] (a network performance measurement tool). We perform a set of experiments where for each host we instruct all other hosts to perform a UDP iPerf measurement to it at the same time for 60 seconds. We sum together the per-second results from each host and present the median of the summed per-second results in the "BW (measured)" row in Table 1. All three of the US hosts are clearly limited to about 1 Gbit/s. IN and NL achieve higher throughput, despite their hosting provider making no claims about their capacity. We present additional pairwise TCP and UDP measurement results in Appendix B.

**Tor Processing Limits:** We evaluate Tor's processing limits to estimate the throughput that a FlashFlow deployment must support in order to measure the fastest Tor relays. We set up a lab experiment that attempts to maximize throughput while minimizing the effect of limiting factors including network latency, congestion and flow control algorithms in TCP and in Tor, the capacity of the underlying network, and the number of Tor circuits and TCP sockets used during the measurement. Over a 120-second measurement, we found that a Tor relay was able to process traffic at a rate of 1.25 Gbit/s in the median while using 20 TCP sockets. We confirmed that Tor reached 100% CPU utilization during this measurement, which is expected because Tor runs all of its cell scheduling code in a single thread. We conclude that the Tor software should not prevent us from measuring even the fastest Tor relay, the claimed capacity of which was 998 Mbit/s in July 2019 [8].

Because we will use our US-SW host to run target relays in our Internet experiments, we also establish ground-truth Tor capacity on it by running an experiment similar to the one described above. We run a relay on US-SW, and use the remaining machines to run Tor processes that support the measurement of US-SW. The target relay on US-SW achieves a maximum median throughput of 890 Mbit/s while consuming 95–100% of a CPU core (again, due to Tor's primarily single-threaded nature). We conclude that this is the fastest we can expect Tor to forward traffic on US-SW.

More details about the above experiments appear in Appendix C. We also provide results in Appendix D from additional experiments that further verify that we can fully measure Tor relay capacity.

**FlashFlow Implementation and Setup:** We implement FlashFlow as a 1,200-line patch to Tor v0.3.5.7 containing measurer- and relay-side measurement support and a 1,300-line C/Rust program that controls FlashFlow measurers. The experimental setup for the remainder of this section is as follows. US-SW runs a single target Tor relay. Some combination of the remaining hosts (US-NW, US-E, IN, and NL) measure the target relay. We configure FlashFlow with the following settings, which were determined through a sequence of experiments detailed in Appendix E: the number of measurement sockets $s = 160$ (the $s$ that maximizes throughput on the slowest host); the multiplier $m = 2.25$ (the smallest $m$ that yields sufficient accuracy); the measurement duration and strategy is to take the median throughput achieved in $t = 30$ seconds (reasonable balance between time-to-result and accuracy); and error bounds of $\varepsilon_1 = 0.20$ and $\varepsilon_2 = 0.05$. We consider the effect of kernel tuning on $s$ in Appendix D.

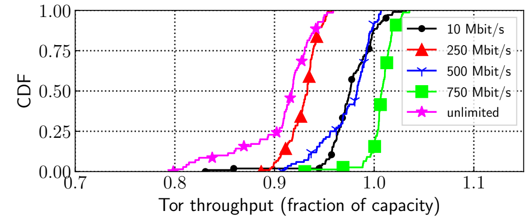



**Figure 6:** Evaluation of FlashFlow's accuracy from 24 hours worth of 30 second experiments with multiplier $m = 2.25$. CDFs are over the median per-second throughput measured by each team.

## 6.2 Measurement Accuracy

We evaluate FlashFlow's accuracy with and without client background traffic.

**Without Client Background Traffic:** We conduct a set of Internet experiments in which we configure a target relay on US-SW and form measurement teams from all possible unique subsets of the remaining machines from Table 1. We set throughput limits of 10, 250, 500, 750, and unlimited Mbit/s on the target; for each such limit we test how well all measurement teams can measure it, where each measurer in each team is limited to its share of the factor $f$ of measurer capacity that is necessary to measure the target using $m = 2.25$. Each such measurement (a team measuring a throughput-limited relay) runs for 30 seconds and is repeated 7 times over the course of 24 hours. The result of each measurement is the median per-second throughput over the 30 second period.

Figure 6 shows the accuracy of our measurements, categorized by the Tor capacities at the target. Across all configured capacities, all but one experiment (99.8%) produces results within $\varepsilon_1 = 0.20$ and $\varepsilon_2 = 0.05$. FlashFlow measures within 11% error (0.89–1.11 times capacity) in 95% of experiments. We provide additional results in Appendix F showing that measurements remain accurate when multiple relays are measured concurrently, which would occur during a full-network Tor measurement by FlashFlow.

**With Client Background Traffic:** To evaluate FlashFlow's ability to measure a relay with realistic client background traffic, we run a Tor relay on US-SW and connect it to the real Tor network.[2] We run the relay for 60 days before starting any FlashFlow measurements so that it is measured by the existing BWAuths, earns the Guard flag, and attracts a significant amount of client traffic (50 Mbit/s on average). The relay is configured to limit its Tor throughput to 250 Mbit/s, and we measure it with one FlashFlow measurer running on NL. Before, during, and after each experiment we record per-second Tor throughput events from the relay that include the total amount of traffic it is forwarding, while during the experiment FlashFlow reports for each second both the amount of measurement traffic that the relay is fowarding as well as the amount of background traffic that it claims to have forwarded.

[2] In practice, we run the relay on a machine with hardware identical to US-SW and in the same datacenter in order to parallelize our experiments.

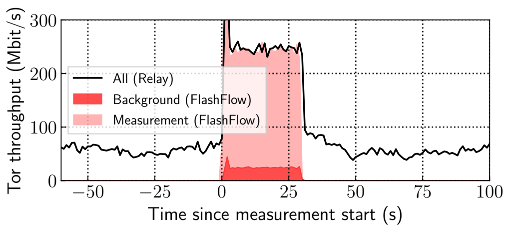
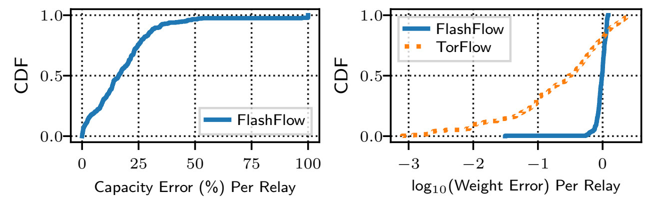



**Figure 7:** Tor throughput during measurements of a relay with client background traffic as reported by the FlashFlow and by the relay. The shaded regions are stacked, and FlashFlow reports their median per-second sum as its result.




**(a)** Relay Capacity Error (Eq. 2) **(b)** Relay Weight Error (Eq. 5)

**Figure 8:** Measurement error during concurrent relay measurement in Shadow simulations. The corresponding network capacity error (Eq. 3) is 14% for FlashFlow, while the corresponding network weight error (Eq. 6) is 4% for FlashFlow and 29% for TorFlow.

Recall from § 4.1 that a Tor relay enforces a maximum ratio $r$ between its regular background traffic and its measurement traffic during a measurement: a higher $r$ allows for more regular traffic and minimizes the effect that the measurement process has on the Tor clients, while a lower $r$ minimizes the advantage a malicious relay has when lying. We evaluate FlashFlow's accuracy under multiple $r$ ratios; we present the results from $r = 0.1$ while noting that the results from the other tested values of $r$ were similar.

Figure 7 confirms that the sum of the background and measurement traffic reported by FlashFlow is equal to the total traffic reported by the relay. Following the measurements, the relay's throughput immediately returns to the level it was before, demonstrating that FlashFlow has no lingering effect on background traffic levels. We also observe in Figure 7 that background traffic is limited to 25 Mbit/s as is expected. Note that the spike at the beginning of the measurement is due to the Tor relay allowing a one second burst before limiting its own throughput to 250 Mbit/s.

We observe that since our relay's background traffic level was 50 Mbit/s with a capacity limited to 250 Mbit/s, we would need to configure $r < 0.2$ in order to cause the relay to withhold background traffic during the FlashFlow measurement. Because relatively high capacity relays with low Tor throughput will not need to limit background traffic, we believe that $r = 0.25$ provides a reasonable trade off for limiting a malicious relay to only inflate their measurement by $1/(1-r) = 1.33$ (see § 5).

## 7 Simulation Experiments

**Network Measurement Efficiency:** We evaluate the efficiency of FlashFlow in measuring the entire Tor network in terms of its speed. To estimate these values, we simulate measurement of the network by a single team. We use a greedy scheduler to determine the fastest that we can measure the entire network. Then we replay the appearance of new relays in the consensus and determine how efficiently they can be measured as well.

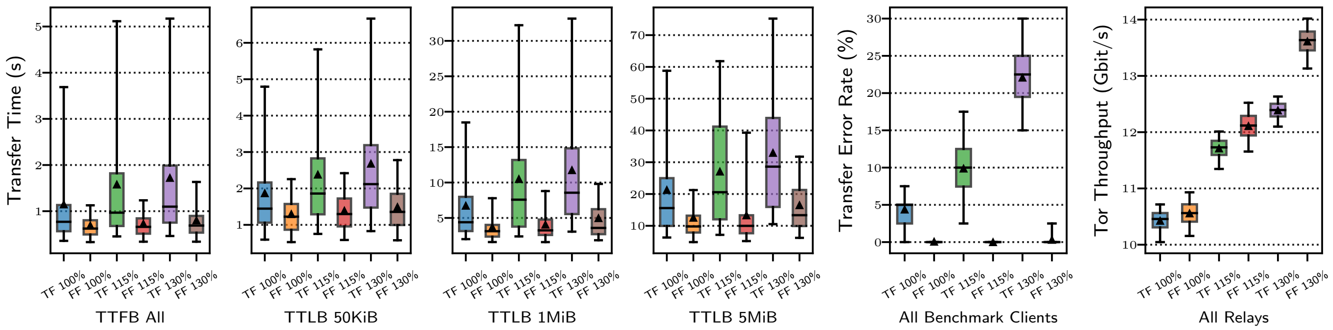
We determine the state of the Tor network over July 2019 using archived Tor consensuses and descriptors [8]. Similar to § 3, we estimate the capacity of relay $r$ at time $t$ to be the minimum of the rate limits set in the relay's descriptor at $t$ and the largest observed bandwidth for $r$ in the period June–August 2019. Among all relays, the largest capacity thus determined for July 2019 is 998 Mbit/s.

We estimate how fast FlashFlow could measure the entire network for each day in July 2019. For this estimate, we use the first consensus in the day, and we assume that all of the relays in the network have been measured before and thus have capacity estimates. We greedily assign relays to each slot in order, with each assignment choosing the largest relay for which there is available capacity to measure. We use a measurement team consisting of 3 measurers with 1 Gbit/s capacity each. This team has capacity that is just larger than the minimum required to accurately measure the largest relay seen, which due to the excess factor $f = 2.84$ and maximum capacity of 0.998 Gbps is 2.84 Gbit/s.

The result for the median day is that 5 hours (i.e. 599 30-second slots) are needed to measure the entire network, with a minimum of 4.9 and a maximum of 5.1. The schedule measures a median of 6,419 relays (min: 6,355, max: 6,528) with a median total capacity of 608 Gbit/s (min: 592, max: 621). This speed suggests that the entire network could be measured at least every 24 hours with significant spare capacity to measure new relays as they join the network.

We next estimate how quickly new relays can be measured. A relay is considered new if it has not been seen in the last month. We consider each consensus in July 2019 and assume relays in the first consensus are not new. During this time, there is a median of 3 new relays in a consensus (min: 0, max: 98). We use as the new-relay capacity estimate the 75th percentile advertised bandwidth from descriptors in June 2019, which is 51 Mbit/s. The simulation result is that the median time to measure new relays in a consensus is 30 seconds (min: 0 minutes, max: 13 minutes). These results show that new relays can be measured within minutes even while FlashFlow re-measures the entire network every 24 hours.

**Network Measurement Accuracy and Performance:** We evaluate FlashFlow in a full Tor network deployment using Shadow [18], a discrete-event network simulator and a standard tool for conducting Tor performance experiments [33]. We configure a private Tor test network in Shadow that is 5%




**(a)** Benchmark Performance **(b)** Benchmark Errors **(c)** Tor Throughput

**Figure 9:** Performance results when using TorFlow (TF) and FlashFlow (FF) weights in Shadow simulations with normal (100%) and extra (115%, 130%) traffic load. (a) Time to first and last byte of 50 KiB, 1 MiB, and 5 MiB transfers by performance benchmark clients. (b) Fraction of benchmark client transfers that failed (timed out). (c) Tor network throughput (for every second, sum of relays' Tor throughput). In the boxplots, the horizontal line shows the median, the triangle shows the mean, the box shows the interquartile range, and the lower and upper whiskers extend to the 5th and the 95th percentile, respectively.

of the size of the public network and contains: 3 DirAuths; 328 relays; 397 TGen clients that use Tor Markov models to generate the traffic flows of 40k Tor users [23]; and 40 TGen clients that mirror Tor's performance benchmarking process by repeatedly downloading 50 KiB, 1 MiB, and 5 MiB files (timeouts are set to 15, 60, and 120 seconds, respectively). The relays were sampled from Tor's consensus files from January 2019 [8] and placed in the closest city in Shadow's Internet map according to IP address and following best practices [20]. Each relay is configured with a capacity equal to the maximum observed bandwidth of the corresponding relay in the public Tor network during January 2019.

To measure accuracy, we first run a base FlashFlow simulation (using our implementation and configuration from § 6) in which FlashFlow uses 3 measurers with capacities of 1 Gbit/s each to measure the Tor network and produce a bandwidth file containing a capacity estimate and weight for each relay. We repeat the simulation with TorFlow, which produces a bandwidth file with weights only (see §2). We use the capacity estimates, weights, and the ground truth throughput of each relay to compute the relay and network measurement errors as described in Equations 2, 3, 5, and 6.

Figure 8 shows the relay capacity and weight error as CDFs over all relays. Although Figure 8a shows that both the median and inter-quartile range of capacity error *across relays* is 16%, the corresponding network capacity error (weighted by the magnitude of the absolute error) is only 14% *in total*. Figure 8b compares the relay weight error for FlashFlow and TorFlow, where $x = 0$ represents ideal relay weighting and each unit on the x-axis represents a $10\times$ increase in error. We observe that more than 80% of relays are underweighted by TorFlow compared to their ground truth capacity, following our conclusions that were drawn from Figure 3 in §3. FlashFlow shows considerable improvement in relay weighting, with a total of only 4% network weight error (Equation 6) compared to 29% for TorFlow.

To measure performance, we use the bandwidth files produced by FlashFlow and TorFlow in the above simulations to run 3 new simulations for each system; one simulation is configured with normal (100%) traffic load, one with 15% extra (115%) traffic load, and one with 30% extra (130%) traffic load. In all simulations, Tor is configured to form a consensus with the previously measured relay weights, and therefore client load is balanced according to these weights.

Figure 9 shows considerable improvement in performance when using the FlashFlow weights compared to TorFlow across *all metrics and benchmarks*. Figure 9a shows that the FlashFlow benchmark clients *outperform* the TorFlow benchmark clients across all transfer sizes: in the 100%-loaded simulations, the median of 50 KiB, 1 MiB, and 5 MiB transfer times decreases by 15%, 29%, and 37%, respectively. FlashFlow also yields more *consistent* client performance: in the 100%-loaded simulations, the standard deviation of 50 KiB, 1 MiB, and 5 MiB transfer times decreases by 55%, 61%, and 41%, respectively. We also observe that FlashFlow better supports *network growth* because the performance improvements increase as the network becomes more loaded. For example, relative to TorFlow, the median 1 MiB transfer time in FlashFlow decreases by an additional 28% and 29% when the network is 15% and 30% more loaded, respectively. Surprisingly, performance in the 130%-loaded FlashFlow simulation was still better than performance in the 100%-loaded TorFlow simulation, across all transfer sizes. Figure 9b shows that the median rate of transfer timeouts decreases by 100% in all FlashFlow simulations, compared to median transfer failure rates of 5%, 10%, and 23% for TorFlow in the 100%-, 115%-, and 130%-loaded simulations, respectively. Finally, Figure 9c shows that the FlashFlow weights result in a more *balanced network* that is more capable of handling additional traffic load. Increasing client-traffic load by 15% and 30% resulted in a 15% and 29% increase in the median Tor throughput (summed over all relays) in FlashFlow as expected, but only a

12% and 18% increase in TorFlow, respectively. Overall, our simulations demonstrate that FlashFlow is significantly more capable of balancing load in Tor than is TorFlow.

## 8 Related Work

**Load Balancing in Tor:** Several systems for load balancing in Tor have been proposed. Load-balancing systems produce the relay weights that clients use to select paths, and in some cases the relay capacities can also be determined. A comparison of these systems appears in Table 2. It shows the added server bandwidth required, the demonstrated success factor of a weight-inflation attack, if the system provides capacity values in addition to weights for load-balancing, and how long it takes to produce weights for the entire network. We observe that for some increase in required server bandwidth, FlashFlow provides increased security and speed, and it can be used for capacity estimates as well as load balancing.

The Tor network currently uses TorFlow [30] to estimate relays' capacities and assign weights accordingly. We discuss TorFlow in § 2 and its limited accuracy in § 3. TorFlow is vulnerable to attacks [11, 25, 36], the most straightforward of which is that a malicious relay can falsely report very high bandwidth information in its descriptor [11], increasing its final weight regardless of its performance measurements. Such attacks have been demonstrated to increase the weight of a Tor relay by 89× [36] to 177× [25]. Data from TorFlow's BWAuths [1, 32] indicate that a single 1 Gbps scanner takes at least 2 days to measure the entire network.

SmarTor [9] decentralizes the operation of the BWAuths using a blockchain and trusted execution environments. Similar to TorFlow, it measures a relay's capacity by downloading a file through the relay in a measurement circuit. It thus remains vulnerable to bandwidth-inflation attacks demonstrated against TorFlow. We do not include SmarTor in Table 2 because its contributions over TorFlow are not to the measurement technique itself. Consequently, its measurement attributes can be assumed to be similar to that of TorFlow.

EigenSpeed [34] uses a peer-measurement approach in which every relay records the average per-stream throughput with every other relay and reports this vector to the Tor DirAuths. The DirAuths combine the vectors into a matrix and iteratively compute the eigenvector of that matrix as the relay weights. For security, this computation must be initialized with the weights from a certain number of trusted relays. During and after the eigenvector computation, relays can be marked as malicious due to atypical changes in or unusual final values of their weights, and these marked relays are effectively removed from the network. EigenSpeed observations are per-flow throughputs rather than total relay capacity.

EigenSpeed is vulnerable to several attacks [25]. First, unevaluated relays receive weights of $1/n$, given $n$ total relays, enabling a Sybil attack to yield disproportionate weights for

**Table 2:** Comparison of Tor load-balancing systems

| | Server BW | Attack Advantage | Capacity Values$^{\star}$ | Speed |
|---|---|---|---|---|
| **TorFlow**$^{\dagger}$ | 1 Gbit/s | 177× | ◐ | 2 days |
| **EigenSpeed** | 0$^{\ddagger}$ | 21.5×$^{\diamond}$ | ○ | 1 day |
| **PeerFlow** | 0$^{\ddagger}$ | 10×$^{\diamond}$ | ◐ | 14 days$^{+}$ |
| **FlashFlow** | 3 Gbit/s | 1.33× | ● | 5 hours |

$^{\star}$ Values provided (●), can be inferred (◐), or unavailable (○).
$^{\dagger}$ SmarTor can be assumed to have attributes similar to TorFlow.
$^{\ddagger}$ Relays measure each other using existing client traffic.
$^{\diamond}$ With 20% trusted relays (by number or weight).
$^{+}$ Time to measure largest 96.8% of relays.

the malicious relays. Second, an *increase framing attack* allows an adversary controlling just 2% of the network to frame up to 20% of the honest relays as malicious and have them removed from the network. Finally, an *targeted liar attack* allows a set of malicious relays to inflate their total weight to 7.4–28.1 times the weight they deserve, depending on the number of trusted relays.

In PeerFlow [25], relays periodically report to the DirAuths the total number of bytes they exchange with each other. The DirAuths then securely aggregate the traffic data to produce relay weights. In the process of determining weights, PeerFlow produces lower bounds on relay capacities that can be used as capacity estimates. PeerFlow requires a fraction $\tau$ of relay weight that is trusted, and the adversary can obtain weights for his relays inflated by a factor of $2/\tau$. If $\tau = 0$, then a sufficiently large adversary (i.e. relative weight above 4%) can eventually get an arbitrarily large relative weight. PeerFlow also limits how quickly a malicious relay's weight can increase from one measurement period to the next. Based on the suggested parameters, a malicious relay can inflate its claimed capacity by a factor of 4.5 (see Theorem 1 of [25]).

In comparison to these systems, FlashFlow has much better protection against weight inflation both in the short term and long term, as it has an inflation factor of 1.33 at all times. It also allows the entire network to be measured in hours rather than days. FlashFlow does require higher measurement-server bandwidth than previous systems, but the requirement is still not high (3 Gbit/s), especially compared to the capacity of the Tor network itself (> 400 Gbit/s).

We note some additional systems superseded by later work or that do not directly produce load-balancing weights. Snader and Borisov [35] propose a simple form of EigenSpeed's peer measurement that takes the median of pairwise speed observations. It uses an unweighted median and is thus vulnerable to a Sybil attack. TightRope [13], assumes that capacity weights already exist for the relays and then considers how to choose paths to optimally balance load. Using differential privacy, the current load on all relays is shared with a server that computes a distribution for clients to use when building new circuits. Wang et al. [37] propose Tor clients use lightweight active measurements that use latency as an indicator for congestion, detect congested relays, and automatically avoid using them.

**Other Related Work:** Speed tests such as Ookla [5] are primarily intended for home users to test the throughput of their devices, wireless router, or their ISP's connection. iPerf [2] can achieve high throughput at the transport layer over both UDP and TCP. Prasad et al. [31] describe bandwidth-estimation techniques, focusing on efficient techniques such as packet pairs and trains. Feamster and Livingood discuss the challenges of Internet throughput measurement even when allowing the measurement to fully utilize bandwidth [16].

## 9 Conclusion

Tor's load-balancing system utilizes self-reported capacity estimates from Tor relays, a process that is vulnerable to malicious reporting. We furthermore show through an analysis of Tor metrics data that these estimates are significantly inaccurate and result in suboptimal load balancing. We then present FlashFlow, a system to actively measure Tor relays with limited effect on normal client traffic. We implement FlashFlow, conduct extensive experiments, and show it accurately, securely, and quickly measures the capacities of Tor network relays. Moreover, we show through simulation that these capacities improve the load-balancing of Tor.

Our results show that FlashFlow could be used today to improve Tor's performance and resource estimates. Furthermore, FlashFlow could be used as a secure basis for incorporating additional dynamic performance measurements. Such measurements, such as per-relay network and CPU utilization, could provide information about *available* (rather than total) capacity that may further improve Tor's load balancing. The FlashFlow measurements would be used as a starting weight, and then the weights would only be reduced, depending on the dynamic measurements. FlashFlow would thus securely limit the weight of any relay while allowing for improved performance via adjustments based on insecure dynamic measurements, such as self-measurements.

## Acknowledgments

This work was supported by the Office of Naval Research.

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## A Relay Capacity and Weight Variation

We extend the TorFlow analysis from § 3 to better understand how relay capacity estimates and relay weights vary across relays and over time.

**Relay Capacity Variation:** A relay with a perfect capacity estimation algorithm would consistently report the same advertised bandwidth. Variation in advertised bandwidths thus indicates inaccurate capacity estimation, which further leads to poor load balancing. Moreover, the resulting variable load leads to unpredictable and frustrating client performance. We use the *relative standard deviation* (RSD) as a measure of the variability in relays' advertised bandwidths over time. We compute the RSD over a sequence of values $V$ as

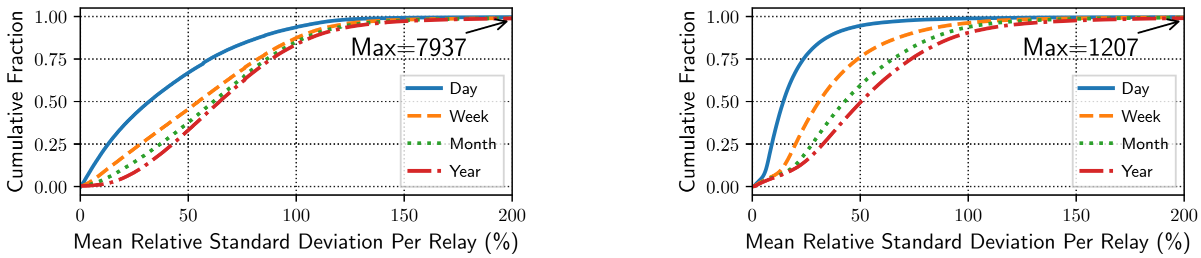
$$\mathrm{RSD}(V) = \mathrm{stdev}(V)/\mathrm{mean}(V), \tag{7}$$

where stdev() and mean() compute the standard deviation and mean, respectively.

Recall from § 3 that $A(r,t)$ is the advertised bandwidth of relay $r$ at time $t$, and that $A(r,t,p)$ is the multiset of advertised bandwidths published during the period of length $p$ preceding time $t$. Varying the length of time $p$ allows us to examine variability over different timescales. We summarize this variability for relay $r$ by computing the mean of $\mathrm{RSD}(A(r,t,p))$ over the times $t$ that are on the hours between 2009-08-01 and 2019-07-31 (we start on 2009-08-01 to provide up to a year of data for periods ending then). The distribution of these means over all relays $r$ appears in Figure 10a for periods $p$ of 1 day, 1 week, 1 month, and 1 year.

Figure 10a shows that the advertised bandwidths reported by relays exhibit significant variation. For the median relay $r$, $\mathrm{RSD}(r,p)$ is 32% when computed for a period length $p$ of a day, and it is 55%, 62%, and 65% when computed for a period length $p$ of a week, month, and year, respectively. Within a given day, there will only be 2–3 descriptors published because they are published every 18 hours. There is thus a surprising amount of variation over a day, which is almost certainly in error due to the very short time interval. For a week, where we also would not expect much change in true capacity, the RSD is 27% or greater for 75% of the relays, and 82% or greater for 25% of relays. The maximum RSD over a year is 7,937%. Advertised bandwidth thus frequently varies a non-trivial amount, and most of this variation is unlikely to be from genuine changes in relay capacity.

**Relay Weight Variation:** Recall that the probability that a relay is selected in a circuit is roughly its normalized consensus



**(a)** Relay Capacity Varation CDF

**(b)** Relay Weight Varation CDF

**Figure 10:** Variation relay capacities and weights over time, computed using 11 years of archived Tor metrics data [8].

weight, that is, its fraction of the total weight assigned to all relays. Recall also that $W(r,t)$ represents this value for relay $r$ at time $t$, and that $W(r,t,p)$ is the multiset of these values over the consensuses during the period of length $p$ preceding time $t$. To measure the variability of normalized consensus weights, we again use the RSD. We compute $\text{RSD}(W(r,t,p))$, following Equation 7, and summarize the results over time by computing its mean over all times $t$ on the hours starting from $t$ = 2009-08-01.

Figure 10b shows the mean RSD per relay for various periods $p$. We observe similar trends as we observed for advertised bandwidths: variation increases as we include more consensus weights in the RSD computation. The RSD for the median relay is 14%, 31%, 43%, and 50% when computed using weights from the preceding day, week, month, and year, respectively. We also find that the RSD for 25% of relays is greater than 23% when using weights from the preceding day, and greater than 73% when using weights from the preceding year. These results indicate that there is also significant variation in normalized consensus weights. Note that while changes in relays' advertised bandwidths will affect their normalized consensus weights, relays joining and leaving the network (i.e., churn) may also affect the weights to some extent.

## B Capacity of Internet Hosts

We measure the network performance of our Internet hosts (first described in § 6) with particular focus on the links between them and US-SW. Over the course of a day we run 24 bidirectional iPerf [2] TCP and UDP measurements for 60 seconds between each host and US-SW and record iPerf's per-second send and receive throughput statistics. To summarize the results, at each second we take the minimum of the amount of sent and received data, take the median of these 60 per-second data points, and list the range of each host's 24 medians in the first two columns of Table 3.

In all cases the maximum UDP iPerf throughput is higher than the TCP iPerf throughput, which is expected because UDP doesn't hold itself back during perceived packetloss and it has fewer headers (thus less overhead). The range of TCP iPerf throughput for all hosts except US-NW includes 800 Mbit/s. US-NW's TCP iPerf throughput is highly varied, and upon inspection of the results, we determine the variability is only in its receive direction; when only considering the send direction, these results show US-NW is capable of sending TCP iPerf traffic at 926–934 Mbit/s.

**Table 3:** Throughput estimation of Internet hosts using iPerf

| | **TCP (Mbit/s)**$^\star$ | **UDP (Mbit/s)**$^\star$ | **UDP (many)**$^\dagger$ |
|---|---|---|---|
| **US-SW** | - | - | 954 |
| **US-NW** | 176–787 | 740–945 | 946 |
| **US-E** | 874–919 | 943–944 | 941 |
| **IN** | 677–819 | 925–955 | 1076 |
| **NL** | 827–880 | 952–956 | 1611 |

$^\star$ Range of 60-second median iPerf throughput measured by US-SW.
$^\dagger$ 60-second median iPerf throughput when saturated by all other hosts.

As these are measurements between a pair of hosts, either host could be a bottleneck. Thus we perform a set of experiments where for each host we instruct all other hosts to perform a UDP iPerf measurement to it at the same time for 60 seconds. We sum together the per-second results from each host and present the median of the summed per-second results in the last column of Table 3. All three of the US hosts are clearly limited to about 1 Gbit/s. IN and NL achieve higher throughputs, and while their hosting provider makes no claim about their capacity, they must have faster than 1 Gbit/s NICs.

## C Tor Processing Limits

In this section, we provide additional details on the experiments we ran in § 6.1 to determine Tor's processing limitation and its effect on the throughout a relay can achieve.

### C.1 Setup

To test Tor, we set up a small test Tor network in a lab environment. On the *target machine* we run the core Tor network, which including one relay that we choose to be the target of our tests. On the *client machine* we run 100 Tor clients, 100 Tor exit relays, a varied number of curl clients, and an nginx webserver. Both machines have 2 Xeon E5-2697V3 CPUs with a maximum frequency of 3.60 GHz, a total of 56 threads, and 256 GiB of RAM. A 10 Gbit/s fiber cable connects them directly. The RTT between the machines

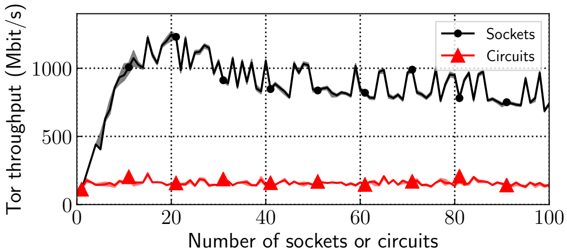



**Figure 11:** Tor throughput at the target relay, varying the number of sockets or circuits. The solid lines are the median per-second throughputs from each 120-second experiment, and the small shaded regions surrounding the lines are the interquartile ranges.

is 0.13 ms.

Because Tor's KIST scheduler is incapable of fully utilizing a high capacity link when it has a a small number of active sockets [17], we investigate the relationship between a relay's number of active sockets and its observed throughput. For 100 *socket* experiments, we instruct $n \in [1,100]$ Tor clients to each build a two hop circuit beginning at the target relay and with the $i$th client's circuit ending at the $i$th Tor exit. We proxy curl processes that download a large file from the webserver over these Tor clients' circuits, and use three curls per circuit (Tor's circuit level flow control prevents too much in flight traffic on a circuit at once, but by running at least two application streams, one will max out the circuit's flow control limit). Note each client opens its own socket to the target relay, thus the target has $n$ busy open sockets to clients.

Regardless of the number of sockets, more circuits should prevent Tor's flow control from inducing a limit, so we also investigate increasing the number of active circuits on a single socket. For 100 *circuit* experiments we instruct a single Tor client to build $n \in [1,100]$ circuits beginning at the target relay and with the $i$th circuit ending at the $i$th Tor exit for $i \in [1,n]$. We again proxy three curls over each circuit to fully utilize each circuit's flow control. Note there is one client, thus the target always has a single busy open socket to a client.

## C.2 Results

Figure 11 shows our results from these two sets of tests. For each number of sockets or circuits, we collect per-second Tor throughput at the target using Tor's BW events for 120 seconds. The median per-second throughputs are plotted together as a solid line. The interquartile ranges nearly imperceptible and plotted as shaded regions above and below each experiment's solid line. While we expected increasing the number of circuits in the *circuits* experiments would increase the throughput at the target, we suspect KIST's single socket throughput limitation prevents additional circuits from increasing throughput.

With 20 sockets in the *sockets* experiments we see the maximum median per-second throughput of 1,248 Mbit/s at the target relay. Tor first consumes 100% usage of a CPU core with 13 sockets, and continues to do so at all higher numbers of sockets. Due to Tor's primarily single-threaded nature, we take this as the ground truth of a relay on this hardware. In the real Tor network, the relay with the highest observed throughput in July 2019 claimed to have forwarded 998 Mbit/s [8]. This may not be a good estimate of the relay's actual capacity (e.g. because it never receives enough client load to reach its capacity), but it establishes a lower bound. With the likely differences in hardware and the limitations of relying on real Tor client throughput demands in mind, 1,248 Mbit/s is a likely approximation of the maximum Tor capacity today. CPUs with faster clock speeds allow for higher Tor capacities, and Tor adding support for multithreaded scheduling would drastically change relays' capacities.

# D TCP Socket Tuning

We investigate tuning the Linux kernel's TCP socket parameters to better support high capacity and high RTT links. With a tuned kernel, theoretically FlashFlow can use fewer measurement sockets across its measurers (its $s$ parameter from Appendix E.1), and fewer sockets would result in less bookkeeping overhead. We first determine the single-socket throughput improvements of a tuned kernel in the lab. Then on the Internet we investigate the effect a tuned kernel has as compared to a default kernel as the number of sockets increases.

## D.1 Single-socket throughput

Notice Figure 11 shows in the *sockets* experiments that opening additional sockets after the maximum Tor throughput is reached lowers the achievable throughput. Figure 14 confirms the same behavior in a different experiment on the Internet. We expect a similar trend affects software in general as the cost of managing many sockets decreases the time available to forward traffic over them and as an increasing number of TCP sockets increasingly interfere with each other for a share of the available link capacity. Regardless, FlashFlow is partially implemented in Tor and is subject to this observed behavior. We are thus motivated to maximize the throughput of a single FlashFlow measurement socket to keep the necessary number of measurement sockets low.

A major limiting factor on a single socket's throughput is the amount of kernel socket buffer memory it is allowed to consume and whether that adequately supports the Bandwidth Delay Product (BDP) of the link. A link's BDP is its network capacity multiplied by its RTT. Despite the high 10 Gbit/s capacity of the link in our lab, its very short 0.13 ms RTT keeps its BDP small at 0.155 MiB. 1 Gbit/s links are increasingly common on the Internet, and a 5th percentile RTT of 27.4 ms [23, §6.1.1] on such a link has a BDP of 3.26 MiB, and a median RTT of 118 ms on a 1 Gibt/s link has a BDP of 14.1 MiB. Higher BDP values for a link mean the hosts on either end must be willing to buffer more "in flight" data

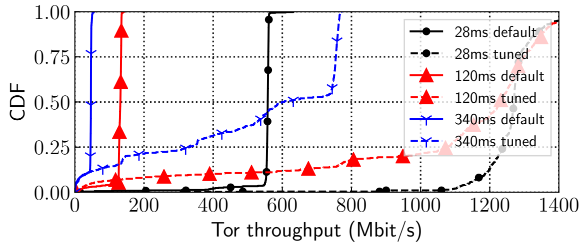



**Figure 12:** Tor throughput at target relay, presented as CDFs of each measurement's 240 per-second throughput data points as measured by FlashFlow with a single measurer socket, with either the default or tuned kernel, and with varied RTT between the target and measurer.

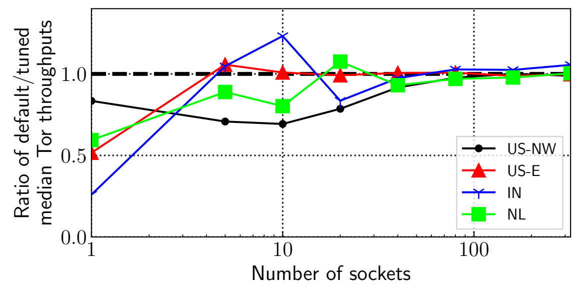



**Figure 13:** Comparison of default kernel and tuned kernel results, presented as ratios. A ratio less than 1 means the tuned kernel helped relative to the same experiment with the default kernel. Tuning the kernel has less of an effect as sockets are added, thus the ratio approaches 1. The x-axis is log scale.

to keep the link throughput near capacity and to wait for acknowledgments. Linux picks default socket buffer parameters on boot based on the host's available system memory; on all our hosts in the lab and on the Internet Linux chooses 4 MiB and 6 MiB for the read and write buffers' maximum sizes respectively. For the experiments in this section, we consider this the *default* kernel parameters, and we consider a second set of *tuned* kernel parameters with a 64 MiB maximum size for both reading and writing.

We run tests with these two configurations on the same pair of lab hosts as described in Appendix C, but add latency between them using netem [3] and vary the amount added to cover the 5th through 95th percentile in the Internet RTT dataset [23, §6.1.1]. On the target host we run a Tor relay, and on the client host we run FlashFlow with a single measurement socket and configured to measure the target for 240 seconds. Figure 12 presents the results as CDFs over each measurement's 240 per-second data points.

As expected, at all RTTs the tuned kernel measurements achieve higher throughput than their corresponding default kernel measurements. Also notice how—for both kernel configurations—as RTT (and thus BDP) increases, the throughput for that kernel decreases as expected. FlashFlow impressively achieves a maximum median throughput of 1,269 Mbit/s, which is consistent with what we find as Tor's capacity in Appendix C.

This shows FlashFlow can achieve extremely high 1 Gbit/s throughput with a single socket and a tuned kernel on Internet links with the Internet dataset's median of 118 ms RTT or less; however, both machines in this setup need to tune their kernels, and we cannot expect Tor relay operators to do this. One can indirectly increase the amount of buffer space available in the kernel by using multiple sockets instead of just one, which we now explore.

## D.2 Multi-socket throughput

Having established a tuned kernel improves single-socket throughput in the lab, we now move to the Internet to investigate how much tuning the kernel helps as the number of measurement sockets increases. At each measurement host individually we use FlashFlow to measure US-SW for 60 seconds, and we consider the case where each uses its *default* kernel and when each uses its *tuned* kernel. For presentation we divide each *default* measurement's result by the corresponding *tuned* result and plot these ratios in Figure 13.

In all cases, for a small number of sockets a tuned kernel results in a higher median throughput than the default kernel, as indicated by ratios less than 1. As the number of sockets used increases, however, tuning the kernel has less of an benefit, and the plots trend towards 1. This is because the amount of memory the kernel allocates to buffer traffic for the increased number of sockets is—in aggregate—able to support the full BDP of the link, nullifying the benefit of allowing larger buffers per socket in the tuned measurements.

# E Deriving Values for FlashFlow Parameters

Before beginning to measure with FlashFlow we run a sequence of experiments to determine appropriate values for its various parameters. First we determine the number of sockets $s$ the measurement hosts should open to measure the target relay, then we explore which multiplier $m$ FlashFlow should use when reserving measurer capacity, we evaluate various measurement durations $t$ and their accuracies, and finally we choose error bounds $\varepsilon_1$ and $\varepsilon_2$.

## E.1 Number of measurement sockets

We now determine a number of sockets $s$ that, in aggregate, FlashFlow measurers should open to the target. We use FlashFlow to measure US-SW for 60 seconds with each measurement host pair wise, varying the number of sockets. We do this until the slowest measurement host stops increasing its throughput.

Figure 14 shows our results. While each host peaks at a different number of sockets, IN is the slowest one to peak,

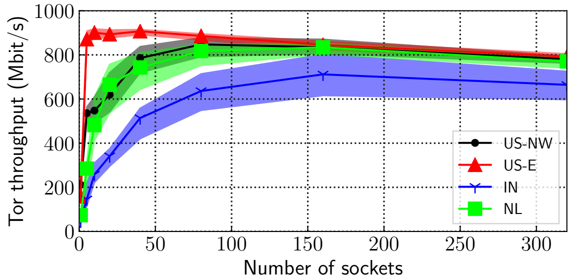



**Figure 14:** Tor throughput at target relay on US-SW as measured by the other machines, varying the number of sockets. Solid lines are median per-second throughput, and the shaded regions are the interquartile range. Default kernel parameters are used.

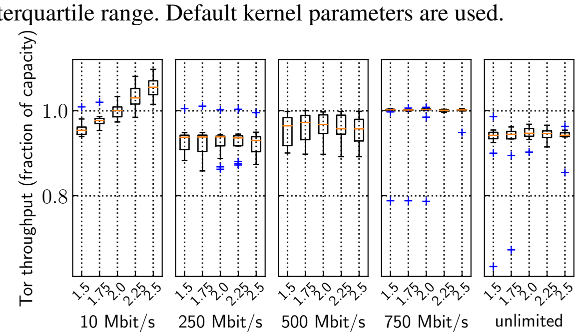



**Figure 15:** Relative Tor throughput as measured by FlashFlow at varied configured limits and with a varied multiplier, presented as a fraction of ground-truth Tor capacity. Boxplots contain all 60 second medians from all subsets with the given multiplier and target capacity.

and does so at 160 sockets. Thus for all future FlashFlow measurements we set the number of sockets $s$ to use across all measurers to 160.

We also observe the relative performance of our hosts in Table 1. We suspect IN produces the slowest measurements because of its high RTT to US-SW, which generally correlates with packet loss and therefore lower throughput, as well as its shared virtual hosting environment in which we do not know and cannot control how many other virtual hosts share its physical host and compete for its CPU and network resources. We suspect the drop in measured throughput after a host's peak is additional CPU overhead of managing multiple sockets. US-E is the only non-virtual host, and it performed better than the others.

## E.2 Multiplier

As FlashFlow runs measurements in parallel, it needs to allocate some amount of Tor capacity at its measurers for each measurement. Recall from § 4.2 that FlashFlow allocates some factor of measurer capacity greater than the relay's existing capacity estimate. This factor depends on a multiplier $m$ for which we now experimentally determine the smallest value that provides sufficient accuracy.

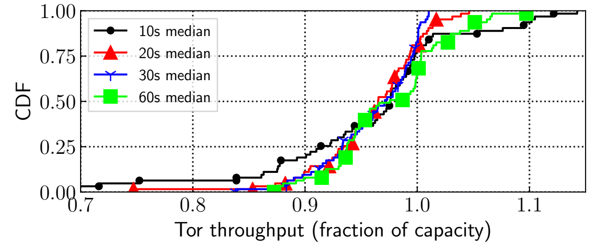



**Figure 16:** Comparison of accuracy of different measurement lengths.

In these experiments we approximate relays of varied capacities by setting Tor's RelayBandwidthRate and RelayBandwidthBurst options to 10, 250, 500, and 750 Mbit/s. Many relay operators use these options limit throughput, and this also simulates relays with such limits at the network layer.

To establish the ground-truth Tor capacity of these throughput-limited relay configurations on US-SW, we rerun the two-hop Tor circuit experiment setup described in Appendix C and § 6.1. At a Tor throughput limit of 10 Mbit/s, we determine a ground-truth Tor capacity of 9.58 Mbit/s, at 250 Mbit/s ground truth is 239 Mbit/s, at 500 Mbit/s ground truth is 494 Mbit/s, and at 750 Mbit/s ground truth is 741 Mbit/s. Recall the ground truth of an unlimited relay on US-SW is 890 Mbit/s.

Having established ground truth, we now consider multipliers of 1.5, 1.75, 2.0, 2.25, and 2.5. For each multiplier and at all capacities, we determine all subsets of measurers with enough measurer capacity to measure the relay, and then we divide that capacity assignment evenly across the measurers in the subset. As an example of a subset, to measure a 500 Mbit/s relay with a multiplier of 1.5 with US-E and IN, we would configure both to limit their throughput to $\frac{494\times1.5}{2}$ Mbit/s. Limiting throughput of FlashFlow measurers is accomplished using the BandwidthRate and BandwidthBurst Tor options.

We present the distribution of results at each target relay throughput limit and each multiplier in Figure 15, normalizing the results as a fraction of their ground-truth Tor capacities. The lowest multiplier that avoids outliers below 80% of ground truth is 2.25. While it has the widest range of results in 10 Mbit/s measurements, the absolute size of this spread is only about 0.8 Mbit/s, which is still quite accurate in absolute terms. For these reasons we choose a multiplier of 2.25 and use it in all future experiments.

## E.3 Measurement duration

Having FlashFlow measure for a shorter time would not only allow it to measure the entire Tor network faster but also prevent it from degrading Tor users' experience for too long when they have a circuit going through a relay being measured. We have been running FlashFlow for 60 seconds in the preceeding sections. We are thus motivated to find a faster strategy that maintains acceptably accurate results.

We consider shorter measurement times using the 2.25 multiplier experiments from the previous section. Each experiment ran for 60 seconds, but we can suppose it ran for a shorter time and take the median. We emulate 10, 20, 30, and 60 second median strategies in this way and present the accuracy of the results in Figure 16. The range of results generally gets larger as measurement times decreases. Interestingly the 30 second median strategy has the smallest range with all results falling between 0.84 and 1.01 times their ground-truth Tor capacity. For this reason and because it is a reasonable balance between time-to-result and accuracy, we choose a measurement length of 30 seconds. See Appendix E.4 for a description of more complex measure strategies we considered but that performed worse.

## E.4 Measurement Strategies

In § E.3 we chose a 30 second measurement duration, after which FlashFlow would take the median per-second throughput as the result of a measurement. We now consider two other strategies.

**Median with ignored lead time:** In this strategy FlashFlow collects per-second throughput for a set duration $d$ as before, but FlashFlow ignores the first $i$ seconds such that it takes the median of the last $d-i$ seconds of data. The motivation is to avoid an initial slow period due to TCP slow start, but because FlashFlow uses many sockets, it generally achieves its maximum throughput immediately (e.g. Figure 7). Consequently, a measurement of duration $d$ with this strategy performs about as well as a simple median strategy of duration $d-i$.

**Dynamic Duration:** We also consider strategies with a dynamic measurement duration. As per-second throughput results are gathered, the data points obtained thus far are viewed in a series of windows. When the median throughput between each window changes less than some factor, the measurement is stopped and the last window's median throughput is the result. This strategy has similar motivations as the previous one, but generally produces worse results than simple medians.

## E.5 Error bounds

All parameters are now determined, but error bounds on what is considered an accurate result are yet to be specified. Recall from § 4.2 that FlashFlow assigns some factor of measurer capacity $f = m(1+\varepsilon_2)/(1-\varepsilon_1)$ times the existing capacity estimate for a relay, where $m$ is the base multipler and $\varepsilon_1$ and $\varepsilon_2$ are the error bounds. Given the chosen measurement duration, 30 seconds, and its minimum/maximum fraction of ground-truth Tor capacity of 0.84/1.01 in Figure 16, we choose error bounds of $\varepsilon_1 = 0.20$ and $\varepsilon_2 = 0.05$ to leave a little room for additional variation when we evaluate FlashFlow's accuracy in § 6.2 and Appendix F.

**Table 4:** FlashFlow estimates during concurrent measurement*

| Limit (Mbit/s) | Capacity (Mbit/s) | Relays (#) | Absolute (Mbit/s) | Relative (%) |
|---|---|---|---|---|
| 100 | 94.2 | 8 | [87.6, 98.9] | [93, 105] |
| 200 | 191 | 4 | [162, 185] | [85, 97] |
| 400 | 393 | 2 | [307, 393] | [78, 100] |

* Relays were run on US-SW, and measurers were run US-E and NL

# F Concurrent Internet Measurements

A FlashFlow deployment measures multiple relays at once in order to speed up the rate at which it can measure the entire network, as described in § 4.3. To evaluate FlashFlow accuracy when measuring relays concurrently, we first establish ground-truth Tor capacity of relays limited with RelayBandwidthRate to 100, 200, and 400 Mbit/s with the same method as in § 6.1: we find ground truth to be 94.2 Mbit/s, 191 Mbit/s, and 393 Mbit/s, respectively. We then run experiments with three sets of throughput-limited relays on US-SW: eight 100 Mbit/s relays, four 200 Mbit/s relays, and two 400 Mbit/s relays. To perform the measurements we choose the measurers US-E and NL as together they have the smallest combined measurer capacity ($941+1611 = 2552$ Mbit/s, see Table 1) greater than the capacity necessary to measure 800 Mbit/s of relay capacity at once ($800 \cdot 2.25[1+0.05]/[1-0.20] = 2362.5$ Mbit/s, see § 4.2). US-E and NL measure eight, four, or two relays at once for 30 seconds; the result is the median per-second throughput.

The experiments and concurrent measurement results are summarized in Table 4. We observe that FlashFlow can measure accurately (within $\varepsilon_1 = 0.20$ and $\varepsilon_2 = 0.05$) in all but one case: one 400 Mbit/s relay measurement fell below $\varepsilon_1 = 0.20$ by a relative factor of 0.02. The remaining estimates are consistent with our accuracy results from measuring single 250 Mbit/s relays at the $m = 2.25$ multiplier (Figures 6 and 15). Therefore, we conclude that measuring relays concurrently does not negatively effect FlashFlow's accuracy.