

Zipper ZMap: Internet-Wide Scanning at 10 Gbps

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Abstract

We introduce optimizations to the ZMap network scanner that achieve a 10-fold increase in maximum scan rate. By parallelizing address generation, introducing an improved blacklisting algorithm, and using zero-copy NIC access, we drive ZMap to nearly the maximum throughput of 10 gigabit Ethernet, almost 15 million probes per second. With these changes, ZMap can comprehensively scan for a single TCP port across the entire public IPv4 address space in 4.5 minutes given adequate upstream bandwidth. We consider the implications of such rapid scanning for both defenders and attackers, and we briefly discuss a range of potential applications.

1 Introduction

In August 2013, we released ZMap, an open-source network scanner designed to quickly perform Internet-wide network surveys [7]. From a single machine, ZMap is capable of scanning at 1.44 million packets per second (Mpps), the theoretical limit of gigabit Ethernet. At this speed, ZMap can complete a scan targeting one TCP port across the entire public IPv4 address space in under 45 minutes—a dramatic improvement compared to weeks [7] or months [8] required using Nmap. Yet even at gigabit linespeed, ZMap does not utilize the full bandwidth of the fastest readily available connections: 10 GigE uplinks are now offered by Amazon EC2 [1] and at a growing number of research institutions.

In this paper, we scale ZMap to 10 GigE speeds by introducing a series of performance enhancements. These optimizations allow scanning speeds that provide higher temporal resolution when conducting Internet-wide surveys and make it possible to quickly complete complex multipacket studies.

Scanning at 10 GigE linespeed necessitates sending nearly 15 Mpps continuously. For single-packet probes such as SYN scans, this allows only 200 cycles per probe

on a 3 GHz core. An L2 cache miss might incur a cost of almost 100 cycles, so it essential to make efficient use of both CPU and memory. In order to generate and transmit packets at this rate, we introduce modifications that target the three most expensive per-probe operations in ZMap:

1. *Parallelized address generation.* ZMap uses a multiplicative cyclic group to iterate over a random permutation of the address space, but this becomes a bottleneck at multigigabit speeds. We implement a mutex-free sharding mechanism that spreads address generation across multiple threads and cores.
2. *Optimized address constraints.* Responsible scanning requires honoring requests from networks that opt out, but over time this can result in large and complex blacklists. We develop an optimized address constraint data structure that allows ZMap to efficiently cycle through allowed targets.
3. *Zero-copy packet transmission.* ZMap sends Ethernet frames using a raw socket, which avoids the kernel’s TCP/IP stack but still incurs a per-packet context switch. We switch to using the PF_RING Zero Copy (ZC) interface, which bypasses the kernel and reduces memory bandwidth.

These enhancements enable ZMap to scan at 14.23 Mpps, 96% of the theoretical limit of 10 GigE. In order to confirm these performance gains, we completed a full scan of the IPv4 address space in 4m29s—to our knowledge, the fastest Internet-wide scan yet reported.

The ability to scan at 10 GigE speeds creates new opportunities for security researchers. It allows for truer snapshots of the state of the Internet by reducing error due to hosts that move or change during the scan. Likewise, it enables more accurate measurement of time-critical phenomena, such as vulnerability patching in the minutes and hours after public disclosure. On the other hand, it raises the possibility that attackers could use 10 GigE to exploit vulnerabilities with alarming speed.

2 Related Work

Many network scanning tools have been introduced [7, 11, 13–15], although until recently most were designed for scanning small networks. One of the most popular is Nmap [15], a highly capable network exploration tool. Nmap is well suited for vertical scans of small networks or individual hosts, but the original ZMap implementation outperformed it on horizontal Internet-wide scans by a factor of 1300 [7]. Our enhancements to ZMap improve its performance by another factor of ten.

ZMap is not the first Internet-wide scanner to use PF_RING to send at speeds greater than 1 Gbps. Masscan, released in September 2013, also utilizes PF_RING and claims the ability to scan at 25 Mpps using dual 10 GigE ports—84% of the theoretical limit of dual 10 GigE [11]. We present a more detailed comparison to Masscan in Section 4.3. While the Masscan team did not have the facilities to perform live network tests at rates higher than 100,000 pps [11], we report what we believe is the first Internet-wide scan conducted at 10 GigE speeds.

3 Performance Optimizations

ZMap achieves this performance based on a series of architectural choices that are geared towards very large, high-speed scans [7]. It avoids per-connection state by embedding tracking information in packet fields that will be echoed by the remote host, using an approach similar to SYN cookies [3]. It eschews timeouts and simplifies flow control by scanning according to a random permutation of the address space. Finally, it avoids the OS’s TCP/IP stack and writes raw Ethernet frames.

This architecture allows ZMap to exceed gigabit Ethernet linespeed on commodity hardware, but there are several bottlenecks that prevent it from fully reaching 10 GigE speeds. ZMap’s address generation is CPU intensive and requires a global lock, adding significant overhead. Blacklisting ranges of addresses is expensive and scales poorly. Sending each packet requires a context switch and unnecessary copies as packets are passed from userspace to the kernel and then to the NIC [9]. We implement optimizations that reduce each of these bottlenecks.

3.1 Address Generation Sharding

Address generation in ZMap is designed to achieve two goals. First, it avoids flooding destination networks by ordering targets according to a pseudorandom permutation of the address space. Second, it enables statistically valid sampling of the address space.

ZMap iterates over a multiplicative group of integers modulo p that represent 32-bit IPv4 addresses. By choosing p to be $2^{32} + 15$, the smallest prime larger than 2^{32} ,

we guarantee that the group $(\mathbb{Z}/p\mathbb{Z})^\times$ is cyclic and that it covers the full IPv4 address space. ZMap derives a new random primitive root g for each scan in order to generate new permutation of the address space. The scanner starts at a random initial address a_0 and calculates $a_{i+1} = g \cdot a_i \bmod p$ to iterate through the permutation. The iteration is complete when a_{i+1} equals a_0 .

The most expensive part of this scheme is the modulo operation, which must be performed at every step of the iteration. Unfortunately, the modulo operation cannot currently be performed by multiple threads at once, because each address in the permutation is dependent on the previous—calculating the next address requires acquiring a lock over the entire iterator state.

To remove this bottleneck and efficiently distribute address generation over multiple cores, we extend ZMap to support sharding. In the context of ZMap, a shard is a partition of the IPv4 address space that can be iterated over independently from other shards; assigning one shard to each thread allows for independent, mutex-free execution. Each shard contains a disjoint subset of the group, with the union of all the shards covering the entire group.

To define n shards, we choose an initial random address a_0 and assign each sequential address a_j in the permutation to shard $j \bmod n$. To implement this, we initialize shards $1 \dots n$ with starting addresses a_0, \dots, a_{n-1} , which can be efficiently calculated as $a_0 \cdot g^{0, \dots, n-1}$. To iterate, we replace g with g^n , which “skips forward” in the permutation by n elements at each step. Each shard computes $a_{i+1} = a_i \cdot g^n \bmod p$ until reaching its shard specific ending address a_{e_j} . For example, if there were three shards, the first would scan $\{a_0, a_3 = g^3 \cdot a_0, a_6 = g^3 \cdot a_3, \dots, a_{e_1}\}$, second $\{a_1, a_4 = g^3 \cdot a_1, a_7 = g^3 \cdot a_4, \dots, a_{e_2}\}$, and third $\{a_2, a_5 = g^3 \cdot a_2, a_8 = g^3 \cdot a_5, \dots, a_{e_3}\}$. We illustrate the process in Figure 1.

After pre-calculating the shard parameters, we only need to store three integers per shard: the starting address a_0 , the ending address a_e , and the current address a_i . The iteration factor g^n and modulus p are the same for all shards. Each thread can then iterate over a single shard independently of the other threads, and no global lock is needed to determine the next address to scan. Multiple shards can operate within the same ZMap process as threads (the configuration we evaluate in this paper), or they can be split across multiple machines in a distributed scanning mode.

Benchmarks To measure the impact of sharding in isolation from our other enhancements, we conducted a series of scans, each covering a 1% sample of the IP address space, using our local blacklist file and a 10 GigE uplink. Without sharding, the average bandwidth utilization over 10 scans was 1.07 Gbps; with sharding, the average increased to 1.80 Gbps, an improvement of 68%.

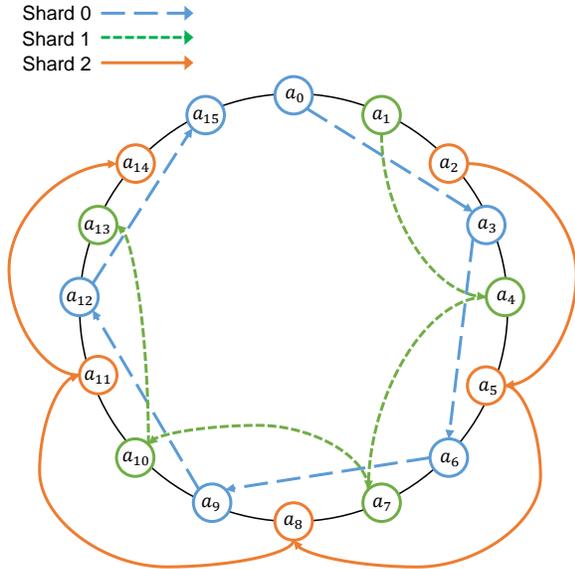


Figure 1: **Sharding Visualization** — This is a configuration with three shards ($n = 3$). Shards 0, 1, 2 are initialized with starting addresses a_0, a_1, a_2 . Each arrow represents performing $a_i \cdot g^3$, a step forward by three elements in the permutation.

3.2 Blacklisting and Whitelisting

ZMap address constraints are used to limit scans to specific areas of the network (whitelisting) or to exclude particular address ranges (blacklisting), such as IANA reserved allocations [12]. Blacklisting can also be used to comply with requests from network operators who want to be excluded from receiving probe traffic. Good Internet citizenship demands that ZMap users honor such requests, but after many scans over a prolonged time period, a user’s blacklist might contain hundreds of excluded prefixes.

Even with complicated address constraints, ZMap must be able to efficiently determine whether any given IP address should be part of the scan. To support 10 GigE linespeed, we implemented a combination tree- and array-based data structure that can efficiently manipulate and query allowed addresses.

The IPv4 address space is modeled as a binary tree, where each node corresponds to a network prefix. For example, the root represents $0.0.0.0/0$, and its children, if present, represent $0.0.0.0/1$ and $128.0.0.0/1$. Each *leaf* is colored either white or black, depending on whether or not the corresponding prefix is allowed to be scanned. ZMap constructs the tree by sequentially processing whitelist and blacklist entries that specify CIDR prefixes. For each prefix, ZMap sets the color of the corresponding leaf, adding new nodes or pruning the tree as necessary.

Querying whether an address may be scanned involves walking the tree, beginning with the most significant bit

of the address, until arriving at a leaf and returning the color. However, a slightly different operation is used during scanning. To make efficient use of the pseudorandom permutation described above, we determine the number of allowed addresses n (which may be much smaller than the address space if a small whitelist is specified) and select a permutation of approximately the same size. We then map from this permutation of $1, \dots, n$ to allowed addresses a_1, \dots, a_n . Each node in the tree maintains the total number of allowed addresses covered by its descendants, allowing us to efficiently find the i th allowed address using a simple recursive procedure.

As a further optimization, after the tree is constructed, we assemble a list of $/20$ prefixes that are entirely allowed and reassign the address indices so that these prefixes are ordered before any other allowed addresses. We then use an array of these prefixes to optimize address lookups. If there are m $/20$ prefixes that are allowed, then the first $m \cdot 2^{12}$ allowed addresses can be returned using only an array lookup, without needing to consult the tree. The $/20$ size was determined empirically as a trade off between lookup speed and memory usage.

3.3 Zero-Copy NIC Access

Despite ZMap’s use of raw Ethernet sockets, sending each probe packet is an expensive operation, as it involves a context switch for the `sendto` system call and requires the scan packet to be transferred through kernel space to the NIC [4, 16]. Even with our other enhancements, the high cost of these in-kernel operations prevented ZMap from reaching above 2 Gbps. To reduce these costs, we reimplemented ZMap’s network functionality using the PF_RING ZC interface [2]. PF_RING ZC allows userspace code to bypass the kernel and have direct “zero-copy” access to the NIC, making it possible to send packets without any context switches or wasted memory bandwidth.

To boost ZMap to 10 GigE speeds, we implemented a new probe transmission architecture on top of PF_RING. This new architecture uses multiple *packet creation* threads that feed into a single *send* thread. We found that using more than one send thread for PF_RING decreased the performance of ZMap, but that a single packet creation thread was not fast enough to reach line speed. By decoupling packet creation from sending, we are able to combine the parallelization benefits of sharding with the speed of PF_RING.

In the original version of ZMap, multiple send threads each generated and sent packets via a thread-specific raw Ethernet socket. We modify thread responsibilities such that each packet creation thread iterates over one address generation shard and generates and queues the packets. In a tight loop, each packet generation loop calculates the next index in the shard, finds the corresponding allowed

Scan Rate	Hit Rate	Duration
1.44 Mpps (≈ 1 GigE)	1.00	42:08
3.00 Mpps	0.99	20:47
4.00 Mpps	0.97	15:38
14.23 Mpps (≈ 10 GigE)	0.63	4:29

Table 1: **Performance of Internet-wide Scans** — We show the scan rate, the normalized hit rate, and the scan duration (m:s) for complete Internet-wide scans performed with optimized ZMap.

IP address using the address constraint tree, and creates an addressed packet in the PF_RING ZC driver’s memory. The packet is added to a per-thread single-producer, single-consumer packet queue. The send thread reads from each packet queue as packets come available, and sends them over the wire using PF_RING.

To determine the optimal number of packet creation threads, we performed a series of tests, scanning for 50 seconds using 1–6 packet creation threads, and measured the send rate. We find the optimal number of threads corresponds with assigning one per physical core.

4 Evaluation

We performed a series of experiments to characterize the behavior of scanning at speeds greater than 1 Gbps. In our test setup, we completed a full scan of the public IPv4 address space in 4m29s on a server with a 10 GigE uplink. However, at full speed the number of scan results (the hit rate) decreased by 37% compared to a scan at 1 Gbps, due to random packet drop. We find that we can scan at speeds of up to 2.7 Gbps before seeing a substantial drop in hit rate.

We performed the following measurements on a Dell PowerEdge R720 with two Intel Xeon E5-2690 2.9 GHz processors (8 physical cores each plus hyper-threading) and 128 GB of memory running Ubuntu 12.04.4 LTS and the 3.2.0-59-generic Linux kernel. We use a single port on a Intel X540-AT2 (rev 01) 10 GigE controller as our scan interface, using the PF_RING-aware `ixgbe` driver bundled with PF_RING 6.0.1. We configured ZMap to use one send thread, one receive thread, one monitor thread, and five packet creation threads.

We used a 10 GigE network connection at the University of Michigan Computer Science and Engineering division connected directly to the building uplink, an aggregated 2×10 GigE channel. Beyond the 10 GigE connection, the only special network configuration arranged was static IP addresses. We note that ZMap’s performance may be different on other networks depending on local congestion and upstream network conditions.

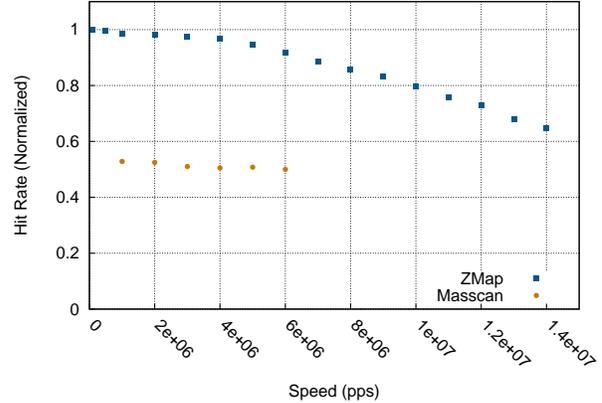


Figure 2: **Hit-rate vs. Scan-rate** — ZMap’s hit rate is roughly stable up to a scan rate of 4 Mpps, then declines linearly. This drop off may be due to upstream network congestion. Even using PF_RING, Masscan is unable to achieve scan rates above 6.4 Mpps on the same hardware and has a much lower hit rate.

We performed all of our experiments using our local blacklist file. Our blacklist, which eliminates non-routable address space and networks that have requested exclusion from scanning [6], consists of over 1,000 entries of various-sized network blocks. It results in 3.7 billion allowed addresses — with almost all the excluded space consisting of IANA reserved allocations.

4.1 Hit-rate vs. Scan-rate

In our original ZMap study, we experimented with various scanning speeds up to gigabit Ethernet line speed (1.44 Mpps) and found no significant effect on the number of results ZMap found [7]. In other words, from our network, ZMap did not appear to miss any results when it ran faster up to gigabit speed.

In order to determine whether hit-rate decreases with speeds higher than 1 Gigabit, we performed 50 second scans at speeds ranging from 0.1–14 Mpps. We performed 3 trials at each scan rate. As can be seen in Figure 2, hit-rate begins to drop linearly after 4 Mpps. At 14 Mpps (close to 10 GigE linespeed), the hit rate is 68% of the hit rate for a 1 GigE scan. However, it is not immediately clear why this packet drop is occurring at these higher speeds — are probe packets dropped by the network, responses dropped by the network, or packets dropped on the scan host due to ZMap?

We first investigate whether response packets are being dropped by ZMap or the network. In the original ZMap work, we found that 99% of hosts respond within 1 second [7]. As such, we would expect that after 1 second, there would be negligible responses. However, as can be seen in Figure 3, there is an unexpected spike in response packets after sending completes at 50 seconds for scans at 10 and 14 Mpps. This spike likely indicates that response

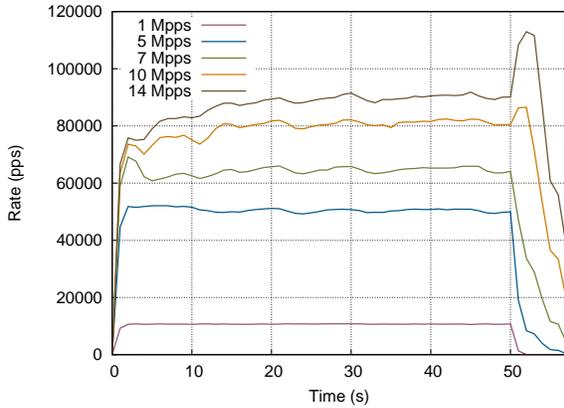


Figure 3: **Response Rate During Scans** — This graph shows the rate of incoming SYN-ACKs during 50-second scans. The peaks at the end (after sending finishes) at rates above 7 Mpps indicate that many responses are being dropped and retransmitted before being recorded by ZMap.

packets are being dropped by our network, NIC, or ZMap, as destination hosts will resend SYN-ACK packets for more than one minute if an ACK or RST packet is not received.

In order to determine whether the drop of response packets is due to ZMap inefficiencies or upstream network congestion, we performed a secondary scan in which we split the probe generation and address processing onto separate machines. The send machine remained the same. The receive machine was an HP ProLiant DL120 G7, with an Intel Xeon E3-1230 processor (4 cores with hyperthreading) and 16 GB of memory, running Ubuntu 12.04.4 LTS and the 3.5.0-52-generic Linux kernel.

As we show in Figure 4, this spike does not occur when processing response packets on a secondary server—instead it closely follows the pattern of the slower scans. This indicates that ZMap is locally dropping response packets. However, the split setup received only 4.3% more packets than the single machine—not enough to account for the 31.7% difference between a 14 Mpps and a 1 Mpps scan. If a large number of response packets were dropped due to network congestion, we would not have observed an immediate drop in responses—likely indicating that the root cause of the decreased hit-rate is dropped probe packets.

It is not immediately clear where probe packets are dropped—it is possible that packets are dropped locally by PF_RING, are dropped by local routers due to congestion, or that we are overwhelming destination networks. PF_RING records locally dropped packets, which remained zero throughout our scans, which indicates that packets are not being dropped locally. In order to locate where packet drop is occurring on our network, we calculated the drop rate per AS and found little AS-level corre-

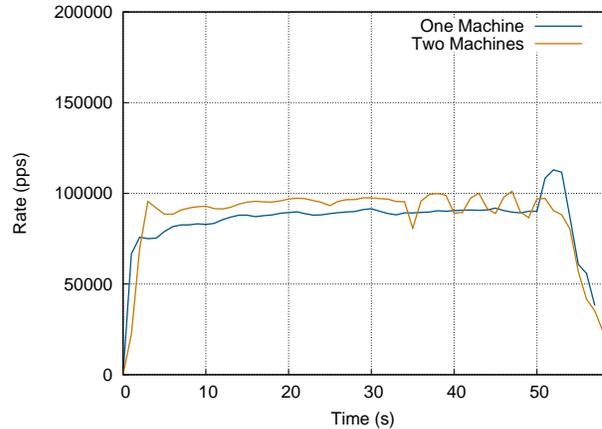


Figure 4: **Comparing One and Two Machines** — If we scan at 14 Mpps and use separate machines for the sending and receiving tasks, the spike in the SYN-ACK rate at 50 s disappears, indicating that fewer packets are dropped with the workload spread over two machines. However, overall the two machine configuration received only 4.3% more responses than with one machine, which suggests that network packet loss accounts for the majority of the drop off at higher scan rates.

lation for packets dropped by the 10 GigE scans, which suggests that random packet drop is occurring close to our network rather than at particular distant destination networks.

4.2 Complete Scans

We completed a full Internet-wide scan, allowing ZMap to operate at its full scan rate. This scan achieved an average 14.23 Mpps—96% of the theoretical limit of 10 GigE, completing in 4 minutes, 29 seconds and achieving a hit rate that is 62.5% of that from a 1 GigE scan. We show a comparison to lower speed scans in Table 1. As we discussed in the previous section, this decrease is likely due to local network congestion, which results in dropped probe packets. However, more investigation is deserved in order to understand the full dynamics of high-speed scans.

4.3 Comparison to Masscan

Masscan advertises the ability to emit probes at 25 Mpps using PF_RING and two 10 GigE adapters, each configured with two RSS queues—84% of linespeed for dual 10 GigE and 166% of linespeed for a single 10 GigE adapter [11]. We benchmarked ZMap and Masscan using the Xeon E3-1230 machine described above. In our experiments, we found that Masscan was able to send at a peak 7.4 Mpps using a single-adapter configuration with two RSS queues, 50% of 10 GigE linespeed. On the same hardware, ZMap is capable of reaching a peak 14.1 Mpps. While Masscan may be able to achieve a higher maxi-

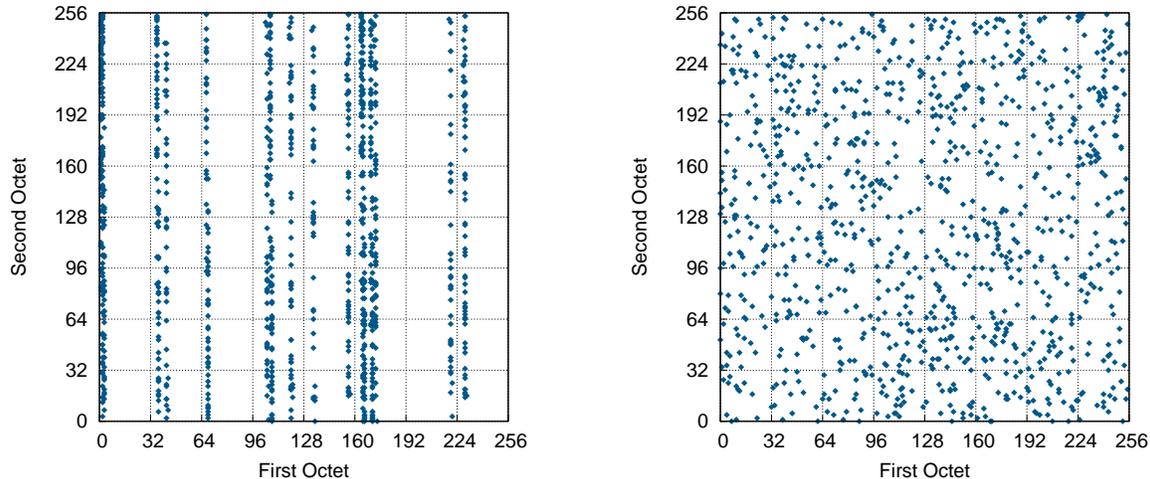


Figure 5: **Address Randomization Comparison** — These plots depict the first 1000 addresses of an Internet-wide scan selected by Masscan (*left*) and ZMap (*right*), with the first and second octets mapped to the x and y coordinates. ZMap’s address randomization is CPU intensive but achieves better statistical properties than the cheaper approach used by Masscan, enabling valid sampling. We enhanced ZMap to distribute address generation across multiple cores.

imum speed using multiple adapters, ZMap is able to fully saturate a 10 GigE uplink with a single adapter.

Masscan uses a custom Feistel network to “encrypt” a monotonically increasing index to generate a random permutation of the IPv4 address space [10]. While this is computation cheaper than using a cyclic group, this technique results in poor statistical properties, which we show in Figure 5. This has two consequences: first, it is not suitable for sampling portions of the address space, and second, there is greater potential for overloading destination networks. This could explain the discrepancy in Figure 2 if Masscan targeted a less populated subnet.

Masscan and ZMap use a similar sharding approach to parallelize address generation and distribute scans. Both programs “count off” addresses into shards by staggering the offsets of the starting position of each shard within the permutation and iterating a fixed number of steps through each of their permutations. In ZMap, this is implemented by replacing the iteration factor g with g^n . In Masscan, this is simply a matter of incrementing the monotonically increasing index by more than one.

5 Applications

In this section, we consider applications that could benefit from 10 GigE scanning and remark on the implications of high-speed scanning for defenders and attackers.

Scanning at faster rates reduces the blur introduced from hosts changing IP addresses by decreasing the number of hosts that may be doubly counted during longer scans. This also increases the ability to discover hosts that are only online briefly. Thus, the ability to complete

scans in minutes allows researchers to more accurately create a snapshot of the Internet at a given moment.

Similarly, the increased scan rate enables researchers to complete high-resolution scans when measuring temporal effects. For example, while researchers were able to complete comprehensive scans for the recent Heartbleed Vulnerability every few hours [5], many sites were patched within the first minutes after disclosure. The ability to scan more rapidly could help shed light on patching behavior within this critical initial period.

Faster scan rates also allow for a variety of new scanning-related applications that require multiple packets, including quickly completing global trace routes or performing operating system fingerprinting. Furthermore, the advancement of single-port scanning can be utilized to quickly perform scans of a large number of ports, allowing scanning all privileged ports on a /16 in under 5 seconds and *all* ports in 5 minutes, assuming the attacker has sufficient bandwidth to the target.

The most alarming malicious potential for 10 GigE scanning lies in its ability to find and exploit vulnerabilities *en masse* in a very short time. Durumeric et al. found that attackers began scanning for the Heartbleed vulnerability within 22 hours of its disclosure [5]. While attackers have utilized botnets and worms in order to complete distributed scans for vulnerabilities, recent work [6] has shown that attackers are now also using ZMap, Masscan, and other scanning technology from bullet-proof hosting providers in order to find vulnerable hosts. The increase in scan rates could allow attackers to complete Internet-wide vulnerability scans in minutes as 10 GigE becomes widely available.

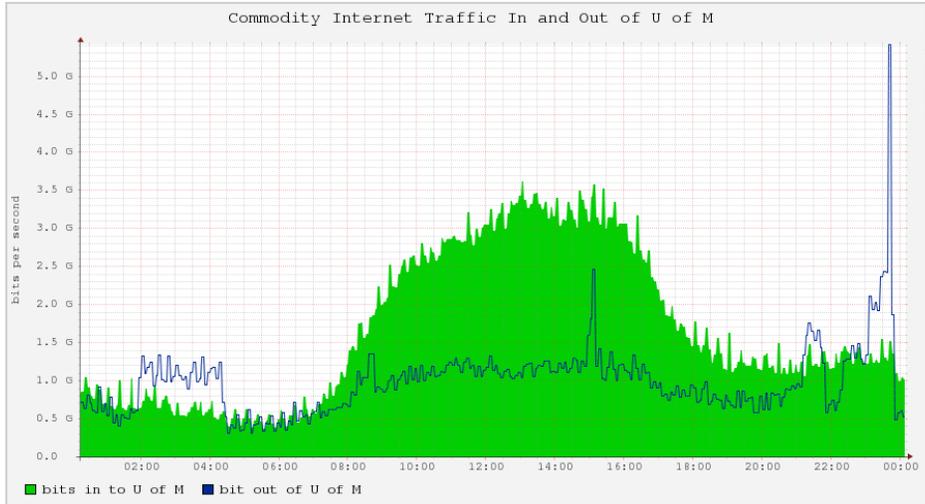


Figure 6: **10 GigE Scan Traffic** — An Internet-wide scan at full 10 GigE speed dwarfed all other traffic at the university during this 24 hour period. At 14.23 Mpps, a single machine running ZMap generated 4.6 Gbps in outgoing IP traffic and scanned the entire public IPv4 address space in 4m29s. The massive increase in outbound traffic appears to have caused elevated packet drop. Notable smaller spikes are due to earlier experiments.

6 Future Work

We demonstrated that it is possible to perform Internet-wide scans at 10 GigE linespeed, but, at least from our institutional network, we are unable to sustain the expected hit rate as scanning approaches this packet rate. Further investigation is needed to understand this effect and profile ZMap’s performance on other networks. One important question is whether the drop off is caused by nearby network bottlenecks (which might be reduced with upgraded network hardware) or whether it arises because such rapid scanning induces congestion on many distant networks—which would represent an inherent limit on scan speed. It is also possible that there are a small number of remote bottlenecks that cause the observed drop in hit rate at high speeds. In that case, identifying, profiling, and removing these bottlenecks could improve performance.

40 GigE hardware currently exists, and 100 GigE is under development [17]. As these networks become more widely available, it may be desirable to optimize and scale Internet-wide scanning to even higher speeds.

7 Conclusion

In this work, we introduced enhancements to the ZMap Internet scanner that enable it to scan at up to 14.2 Mpps. The three modifications we present—sharding, optimized address constraints, and integration with PF_RING ZC—enable scanning at close to 10 GigE linespeed. These modifications are available now on experimental ZMap branches and will be merged into mainline ZMap.

With these enhancements, we are able to complete a scan of the public IPv4 address space in 4m29s. However, despite having a well provisioned upstream network, coverage in our experiments drops precipitously when scanning faster than 4 Mpps. While further research is needed to better characterize and reduce the causes of this drop off, it may be related to specific conditions on our network.

As faster network infrastructure becomes more widely available, 10 GigE scanning will enable powerful new applications for both researchers and attackers.

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References

- [1] Amazon EC2 Instance Types. <http://aws.amazon.com/ec2/instance-types/>.
- [2] Introducing PF_RING ZC. ntop Blog, Apr. 2014. http://www.ntop.org/pf_ring/introducing-pf_ring-zc-zero-copy/.
- [3] D. J. Bernstein. SYN cookies. <http://cr.yp.to/syncookies.html>, 1996.
- [4] L. Deri. Improving passive packet capture: Beyond device polling. In *4th International System Administration and Network Engineering Conference (SANE)*, 2004.
- [5] Z. Durumeric, D. Adrian, M. Bailey, and J. A. Halderman. Heartbleed bug health report, Apr. 2014. <https://zmap.io/heartbleed>.
- [6] Z. Durumeric, M. Bailey, and J. A. Halderman. An Internet-wide view of Internet-wide scanning. In *Proc. 23rd USENIX Security Symposium*, Aug. 2014.
- [7] Z. Durumeric, E. Wustrow, and J. A. Halderman. ZMap: Fast Internet-wide scanning and its security applications. In *Proc. 22nd USENIX Security Symposium*, Aug. 2013.
- [8] P. Eckersley and J. Burns. An Observatory for the SSLiverse. In *Proc. DEFCON 18*, July 2010.
- [9] F. Fusco and L. Deri. High speed network traffic analysis with commodity multi-core systems. In *Proc. 10th ACM SIGCOMM conference on Internet measurement*, Nov. 2010.
- [10] R. Graham. Masscan: Designing my own crypto. Errata Security blog, Dec. 2013. <http://blog.erratasec.com/2013/12/masscan-designing-my-own-crypto.html>.
- [11] R. Graham. Masscan: The entire Internet in 3 minutes. Errata Security blog, Sept. 2013. <http://blog.erratasec.com/2013/09/masscan-entire-internet-in-3-minutes.html>.
- [12] IANA. IPv4 address space registry. <http://www.iana.org/assignments/ipv4-address-space/ipv4-address-space.xml>.
- [13] D. Kaminsky. Paketto simplified (1.0), Nov. 2002. <http://dankaminsky.com/2002/11/18/77/>.
- [14] R. E. Lee. Unicornscan. <http://unicornscan.org>.
- [15] G. F. Lyon. *Nmap Network Scanning: The Official Nmap Project Guide to Network Discovery and Security Scanning*. Insecure, USA, 2009.
- [16] L. Rizzo, L. Deri, and A. Cardigliano. 10 Gbit/s line rate packet processing using commodity hardware: Survey and new proposals. <http://luca.ntop.org/10g.pdf>.
- [17] S. J. Vaughan-Nichols. Here comes the 100GigE Internet. *ZDNet*, 2010. <http://www.zdnet.com/blog/networking/here-comes-the-100gige-internet/334>.