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An Internet Heartbeat

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Abstract—Obtaining sound inferences over remote networks via active or passive measurements is difficult. Active measurement campaigns face challenges of load, coverage, and visibility. Passive measurements require a privileged vantage point. Even networks under our own control too often remain poorly understood and hard to diagnose. As a step toward the democratization of Internet measurement, we consider the inferential power possible were the network to include a constant and predictable stream of dedicated lightweight measurement traffic. We posit an Internet “heartbeat,” which nodes periodically send to random destinations, and show how aggregating heartbeats facilitates introspection into parts of the network that are today generally obtuse. We explore the design space of an Internet heartbeat, potential use cases, incentives, and paths to deployment.

1. INTRODUCTION

Much recent effort has gone into developing an understanding of the presence and properties of *all* end hosts on the Internet using three primary strategies. The first strategy is active scanning, whereby probes are sent to every IPv4 address and responses are collected [23, 18]. The second strategy is for providers with large footprints (e.g., Google or Akamai) to collect information about the client devices (and their networks) that request service [36, 21]. The final strategy is to monitor “background radiation” arriving at a swath of unused address space (network telescopes) [41, 13, 31]. Each of these strategies is helpful in understanding the Internet in-the-large, but each also has significant drawbacks in terms of coverage, feasibility, visibility, and inferential power. For instance, scanning probes are frequently considered abusive and blocked, are unlikely to traverse middle-boxes, and require large amounts of probing, while deriving an understanding from observing legitimate client requests requires a massive global footprint, and hence the information is concentrated in few hands. Finally, using telescopes depends on hosts accidentally sending traffic to the unused address space being monitored.

In this position paper we advocate for a new strategy: an *Internet Heartbeat* (IHB). Rather than relying on happenstance—e.g., a packet arrival at a darknet—or trying to look in from the outside—e.g., trying to reach each host with a probe—

we explicitly bring all hosts into the measurement process by calling for them to transmit a continuous, low-rate stream of messages into the network. This allows endpoints or observers along the path to expect these messages and, hence, gain valuable insight into the network.

At a high-level—which we refine below—any node with a network stack can source and receive IHBs. Participating hosts periodically send a packet to a random destination that includes various metadata. Observation points—anything from a single host to a border router to a backbone link—can examine these packets to facilitate introspection into myriad parts of the network, including those that are today generally not observable and for which there is no longitudinal data. While simple, we believe that an IHB is a powerful mechanism that will enable operators, researchers, and policy-makers to make more informed and complete inferences over the network, as well as support new functionality. Further, IHBs can directly benefit users who currently have only limited insight into their network’s reliability, performance, and availability, and still struggle to distinguish between network problems originating locally, remotely, or with their provider. In particular IHBs enable:

- Any observer to have a global view akin to large providers who make strong inferences from client traffic [36, 21].
- Common measurements to be made passively—at the IHB receiver—without issues of completeness, locality, or blocking.
- Continuity, enabling longitudinal measurement, inferences, and learning rather than a myriad of one-off surveys and on-demand measurement campaigns.
- Stronger inferences, that are easier to reason over, than possible via opportunistic measurements.
- Users to gain insight into their own network’s reliability, and performance, while providing diagnostic capabilities, thereby encouraging deployment.

In this position paper, we sketch the design space of an IHB and consider its potential via candidate use cases, as well as overhead, feasibility, and deployment issues.

2. RELATED WORK

Significant prior literature focuses on performing passive measurement inferences. In addition to legitimate traffic,

non-trivial levels of “background radiation” [41] arrive at networks due to self-propagating malware, security scanners, and attacks. Casado et al. show the wealth of information that can be gleaned passively [9], while Durairajan et al. leverage NTP server logs to estimate Internet latencies [17]. Dainotti et al. demonstrate how background radiation [31] provides insight into global outage and censorship events [13]. Finally, Sargent et al. infer network policies from traffic arriving at darknets [37]. While such opportunistic measurement is powerful, analysis and inference is complicated by the vagaries of attacks, the spread and mitigation of malware, and what networks are affected. In addition to generalizing opportunistic measurement, we show that periodic IHBs permit stronger probabilistic inferences.

Individual networks frequently perform regular pair-wise measurements between nodes or networks under their control, e.g., Content Distribution Networks (CDNs) that run continual measurements to detect and route around path problems [33]. The IHB seeks to push such functionality deeper into the network stack such that all networks are empowered with such knowledge without having to implement their own application-layer protocols and measurements. As importantly, the IHB disseminates global knowledge about the Internet, rather than focusing on an individual network.

Related in spirit to our heartbeats are BGP beacons [29]. BGP beacons are periodic announcements and withdrawals of specific prefixes for the explicit purpose of measuring and understanding real-world BGP behavior and dynamics. BGP beacons have served as enablers of important research efforts to understand and improve routing, e.g., [40]. In a similar fashion, our hope is that the IHB enables new measurements and insights into the global Internet.

Finally, we note that many distributed systems employ the “heartbeat” notion—i.e., a periodic signal to assert liveness [35, 25, 4, 39] and achieve reliability. A key motivation for heartbeats is that a node cannot rely on naturally occurring, event-driven protocol messages to ascertain another node’s health as silent failures or system changes cannot be detected [26]. Our work extends the heartbeat notion to the Internet.

3. IHB DESIGN

As early-stage work, we elect to explore various design alternatives. In general, we follow designs that use existing protocols, are incrementally deployable (today), permit probabilistic inference, and minimize the security burden.

3.1 Transport Protocol

Choosing which transport protocol IHBs should use involves a complex set of tradeoffs. A new transport protocol number would cleanly enable IHBs over IP, but would likely cause IHBs to be discarded or treated differently by today’s network [14]. Similarly, adding IHBs as an IP option is not feasible due to network ossification [22]. While using UDP or TCP for IHBs more closely mimics application traffic, it also brings increased scrutiny from middleboxes and

the possibility of unwanted manipulation [14]. While ICMP is a well-established diagnostic and error reporting protocol, networks may treat ICMPs differently than transports—like UDP or TCP—that applications often use.

In our mock IHB implementation, we use ICMP with a new ICMP type, but plan to experiment with other transports. Our primary design criterion is to design the IHBs such that they are readily and cheaply detectable, and therefore easy to block or capture regardless of transport protocol.

3.2 Meta-Information

A heartbeat without any payload demonstrates reachability and liveness from the source to the observation point. However, including additional meta-data aids interpretation and expands the possible inferences that can be drawn from IHB arrivals. Here we describe four candidate pieces of IHB meta-data¹.

Heart Rate: We include the rate at which the host is sourcing IHBs and information about how destination addresses are chosen (see § 3.3). While an observer may be able to infer the sending rate of each IHB host, the period between heartbeats is expected to be long enough—see next section—that this may be a long and error-prone process, and especially brittle during failures or outages. Further, senders may wish to adapt the rate at which they inject heartbeats dynamically, and on short time scales. By explicitly including the IHB sending rate we can allow observers to set expectations appropriately and stake inferences around the actual rate instead of an estimated rate.

HostID: A well-known facet of the modern Internet is that IP addresses serve as poor host identifiers—due to network address translation (NAT), middleboxes, IPv6 privacy addresses, and aliases. Therefore, we adopt the notion of a “HostID” from Allman et al. [2] and include a small (e.g., 16-bit) identifier in each heartbeat payload. The HostID is randomly generated by the source of the IHB and can be changed over time². A host identifier raises immediate security and privacy concerns. As observed in [2], these issues can be mitigated by using a HostID that is purposefully small such that identifier collisions are common. This means the HostID is meaningless in a global sense, but must be coupled with the IP address to draw inferences about a host’s behavior. For instance, the HostID permits an approximation of the number of hosts behind a NAT.

Originating TTL: Including the TTL with which the heartbeat was sent removes ambiguity of scope and allows both the recipient and observers along the path to determine how far the heartbeat has traveled. We utilize TTL values to infer path changes in §4.3.

Timestamp: The timestamp permits one-way latency approximation when the source and observer’s clocks are synchronized, but further allows observers to note latency *changes* over time even without synchronization.

¹IHBs will be extensible to accommodate new functionality.

²The meta-data could include time since the HostID changed.

3.3 Heartbeat Destination

The intuitive notion is that IHBs should be transmitted around the network uniformly at random. We consider two aspects of choosing the destination: (i) the pool of addresses from which to choose; and (ii) the order of using the addresses in the pool. Here we consider three pools:

Entire Address Space: This pool consists of all 2^{32} IPv4 addresses. In this case, the goal is for all hosts to exchange IHBs with all other hosts on the network. Assuming one host per IP address and full address usage, this goal requires 2^{64} IHBs. Note, however, that the number of IHBs required for full coverage decreases in proportion to the size of the observation point lens, e.g., as discussed in detail in §5.1, a large darknet (monitoring $1/8$ of IPv4 address space) can expect to receive a heartbeat from an arbitrary host after every $\frac{2^8}{2} = 128$ heartbeats it sends.

All /24 Networks: This pool consists of all 2^{24} IPv4 /24 network blocks. This strategy leverages the fact that a /24 address block is the smallest block that can be confidently routed across the Internet. Therefore, IHBs to multiple hosts within a /24 largely share fate. While this is not always true—e.g., end host firewall configurations can vary across hosts within a /24—the relaxed goal results in 2^{48} IHBs to satisfy the goal—or, $\frac{1}{64K}$ -th of the number needed for all hosts to exchange IHBs. Another benefit of using a /24 pool is that all IHB hosts within a /24 could *cooperate* to meet the goal. For instance, if 32 hosts within a /24 send IHBs then each would have to send $524K (\frac{2^{24}}{2^{19}})$ messages to cover the remote /24 address blocks.

Local Subnet: This pool consists of the host’s local network, and would be used as a *Local Heartbeat* (LHB). For instance, a typical home network using the private 192.168.0.0/24 subnet would have 255 different LHB target addresses, while the home network’s public gateway (connected to the provider) might be part of a /22 subnet and, hence, have 1024 LHB targets. In general, LHBs would be sent with a restrictive TTL and be used for local debugging and diagnostics. A refinement of the LHB idea is to make the TTL inversely proportional number of matching most significant bits between the source and the randomly chosen target.

Next, we consider the order in which hosts are probed:

Pure Random: Choosing an entirely random destination from the pool is simple to implement, ensures uniform coverage in time and space, and facilitates inferences with confidence bounds.³

Random Permutation: Rather than choosing addresses at random, the sender could instead randomly permute the entire pool. The random permutation ensures that every destination is used before any destination is repeated. Additionally, the sequence can deterministically repeat once the host has sent to every address, thereby adding additional predictability to the potential inferences.

The above discussion is in terms of IPv4 address space.

³With /24 pools, a /24 is chosen at random and then we independently choose the low order octet of the address at random.

Sending IHBs over IPv6 networks will require understanding the general usage of address blocks (as discussed in [11]), understanding which blocks of IPv6 addresses are routed or having some form of carefully curated hit-list. We discuss possibilities for IPv6 heartbeats in §5.4.

3.4 Source Address

Many Internet-connected devices have multiple interfaces, e.g., WiFi and cellular, while routers have more than one interface by definition. We explicitly envision routers participating in the IHB via their control plane network stack. To expose these interfaces, and the paths they utilize, the IHB should effectively run independent instances of the heartbeat protocol on each physical or virtual interface, and use the interface’s assigned IP address as the heartbeat source. However, the IHB meta-data, in particular the HostID, should be consistent among interfaces.

3.5 Rate

The rate at which a device sources IHBs is a local policy decision and is explicitly included within the heartbeat meta-data so that observers can form concrete expectations over when the next heartbeat should arrive. A possible enhancement to this strategy is to source two back-to-back heartbeats for each destination. While doing so doubles the data rate—or halves the number of IHB recipients per time unit—it enables basic packet-pair dispersion techniques for e.g., estimating path capacity [16].

3.6 Integrity

As a connectionless protocol, the IHB as specified is trivially spoofed. An adversary could source heartbeats with a spoofed source IP address in order to pollute inferences, for instance to make it appear as though a network is up when it is, in fact, suffering an outage. While ingress filtering [20] can mitigate the ability to spoof in some cases, its deployment is not ubiquitous and spoofing remains a present concern [7]. However, an observation point that receives conflicting heartbeat information (arrival rate, TTL, or HostID) from a given source or network can infer that some of the IHBs are illegitimate (and should be ignored).

Even stronger forms of integrity protection may be feasible. For instance, while we do not wish to depend on public key cryptography (for reasons of speed and PKI deployment obstacles), we could utilize heartbeats themselves to distribute shared secrets. Here, heartbeats would include a per-target or per-/24 random key in the meta-data. When subsequently sourcing heartbeats, the host would include a keyed integrity check (such as an HMAC) using the previously received key. In this fashion, an adversary can still spoof heartbeats, but cannot do so undetected unless she has access to the heartbeats arriving at the remote network. Alternatively, IHBs may include *chained* integrity using ephemeral secrets, where the integrity key to the i ’th IHB is contained in the $i + 1$ ’th heartbeat. We plan to explore options for heartbeat integrity more completely in future work.

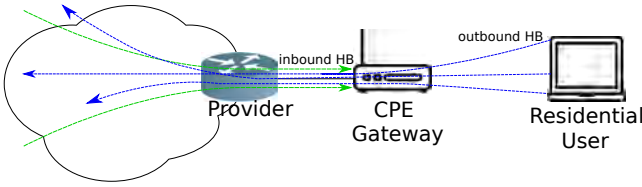


Figure 1: Inbound and outbound IHBs enable users to better diagnose problems and localize their origin, while facilitating longitudinal measurements of their provider’s availability and reliability.

4. USE CASES

To shed light on potential inferences possible with an IHB, we explore three use-cases: outage detection, residential broadband debugging, and forwarding path changes.

4.1 Outage Detection

An increasingly important global measurement task is identifying Internet outages. Traditional methods of outage detection rely on passively monitoring BGP [15] or performing large-scale active measurements [34]. Unfortunately, many outage events do not present as BGP activity, while active measurements require significant and continual probing. In contrast, an IHB inherently provides a means for understanding the data-plane reachability of remote networks simply by making inferences over the sequence of heartbeats received.

Naturally, different vantage points will be able to make stronger, and faster, inferences than others. For example, consider again a /8 darknet where we wish to monitor the reachability of a remote /24 subnet. Assume that only a single host on the remote /24 participates in the IHB at a rate of 1 pps. Thus, every second there is a $\frac{1}{2^8}$ probability that the node sends a heartbeat to a destination in the /8 monitored by the darknet. After k seconds the probability that the /8 receives no heartbeats from this host is: $(1 - \frac{1}{2^8})^k$. Thus, the probability that the remote /24 is reachable even though the darknet has received no heartbeats after $k = 100$ seconds is approximately 67%. However, the likelihood of not receiving a heartbeat by chance rapidly decreases over time: there is only a 3% chance that the /24 is reachable after receiving no heartbeats for 15 minutes.

Of course, more hosts participating in the IHB on the remote /24 increase the outage sensitivity and confidence, while smaller darknets decrease detection ability. The rough numbers in the preceding example are meant to highlight what is possible given realistic assumptions over IHB adoption and the size of today’s darknets. The key point is that the periodic behavior of IHBs permits reliable probabilistic inference where conscious engineering tradeoffs can be made given the required detection sensitivity.

4.2 Residential Broadband

We want IHBs to benefit not just researchers and operators, but also the hosts and—most importantly—users who participate in the sourcing and receiving of heartbeats. As an example of aligning IHBs with user incentives, we consider

IHB use within residential networks.

While there has been significant recent effort toward understanding residential broadband speed and performance [5, 28], less is known about the reliability of these networks. This is particularly true for broadband customers who: (i) will only notice network failures if they occur when the user is home and trying to use the network; (ii) do not maintain long-term statistics over their connection’s reliability or provider’s availability; and (iii) cannot distinguish between a network failure within their home, in the access network, or occurring remotely (i.e., outside of the control of the provider). IHBs provide a means to enable continuous monitoring of a customer’s home access network, while introspection of IHBs facilitate diagnostics and the ability to measure adherence to service level agreements.

Assume that a broadband user’s home CPE gateway inspects both inbound and outbound heartbeats and further computes statistics and metrics over the heartbeats for the user. In Figure 1, inbound IHBs and LHBs arrive at the customer’s CPE (in §5.1, we explore the expected rate of incoming heartbeats—the salient feature here is that a constant stream of heartbeats arrive at the CPE). Further, the CPE observes outbound heartbeats sent by host(s) on the user’s local network (either IHBs or LHBs). These outbound heartbeats provide evidence that the user’s clients are able to obtain an address and reach the gateway.

The heartbeats immediately provide valuable information to the CPE, which can be exposed to the user (e.g., through a user-friendly web interface). Employing the same probabilistic methods as for outage detection (§4.1), the CPE can thus aid in isolating whether reachability issues are local, on the user’s access connection, within the user’s provider, or remote. We further envision the CPE providing information to the user over: (i) the reliability of the connection to her provider; (ii) evidence of which networks could reach the user at a given point in time; and (iii) evolution of latencies from particular hosts and networks.

These inferences can be further strengthened by obtaining additional evidence from other hosts on the same subnetwork through LHBs if these LHBs work to distribute knowledge about IHBs received among all hosts on the subnet.

4.3 Path changes

Heartbeats can reveal both global and specific forwarding dynamics within the network via simple analysis of the IP time-to-live (TTL). Because routers decrement the TTL before forwarding the packet, the TTL provides an approximation of the number of hops from the source to the observation point. TTL changes for the same source or network are thus indicative of routing changes or load-balancing, allowing heartbeats to serve as a path change detection mechanism. Importantly, aggregation and correlation of heartbeats can identify networks that share paths and share fate.

As an expository example, we sent heartbeats from 26 Planetlab nodes [10] toward random addresses of a darknet

over a six day period. While the TTL of received heartbeats from 16 of the nodes remained constant over the collection period, the TTL changed for 10 of the sources. Heartbeats from three of the ten planetlab sources had an equal distribution of TTL values, revealing the presence of load-balanced paths. A time-correlated heartbeat TTL change was observed among three of the sources and lasted for approximately one hour. Because this path change did not affect all heartbeats, the routing change was distant to the telescope. However, the correlated change suggests that the three nodes share a path in the network core, and illustrates the potential inferential power of tomography techniques [15] combined with IHBs.

Last, path changes can serve as a rough indicator of potentially malicious traffic. While IP source address spoofing [7] allows an attacker to impersonate an address, the attacker cannot set her packet’s initial TTL such that she is topologically closer than the number of router hops. As such, packets that arrive with a TTL less than previously observed from that network may be due to a routing change, or may indicate spoofing. If heartbeat packets arrive from a host with one TTL while TCP SYN packets or DNS packets arrive with a different TTL, this further suggests the presence of spoofing.

4.4 Additional applications

The preceding use cases highlight possible applications of IHBs; we believe they can enable other uses including:

Traffic optimization: A well-known property of Internet routing is that alternative paths and indirection can provide superior end-to-end performance [3]. CDNs and service providers therefore routinely perform measurements to inform their path selection [33]. IHBs expose information (loss, capacity) to receivers about available paths and their performance. We envision network overlays (e.g., DHTs, peer-to-peer, and Tor) using IHBs to inform their overlay construction without the need for dedicated active probing.

Census: Network census campaigns, e.g., [23], have seen significant interest in applications ranging from vulnerability analysis [18] to hitlist generation [19] to estimating address space usage [12]. Whereas these existing techniques require significant active probing (where load is concentrated at the probing host) and suffer from completeness and coverage issues, an IHB naturally facilitates these studies in a highly distributed and continual fashion.

Alias resolution: In §3.4, we note that devices with multiple interfaces should run an IHB instance on each. Because the HostID is tied to the host rather than the interface, we imagine the ability to perform probabilistic alias resolution, the process of identifying the set of IP addresses belonging to a single physical device such as a router [27]. Whereas alias resolution is today an expensive, time-consuming, incomplete, and error-prone task [27], a passive heartbeat observation point can easily identify candidate aliases by clustering source addresses of heartbeats with the same HostID. Naturally, this set of candidate aliases will initially be very large—due to the small HostID identifier space—but can be

refined over time as stacks choose new random HostIDs or can be combined with other information such as traceroute data to detect aliases.

Policy inference: Work on understanding differential traffic treatment or blocking frequently uses multiple vantage points to compare results [8]. Similarly, comparing IHBs that arrive at different collection points can shed light into different network policies⁴. For instance, if we observe IHB packets arriving from source network S at destination network X , but no IHB packets arriving from S to network Y , then something is blocking traffic from S to Y . Using additional IHBs and network tomography [15] may further isolate network policy.

5. DISCUSSION

Although the IHB is largely a thought experiment at this time, we discuss practical deployment issues next.

5.1 Overhead

To demonstrate the back-of-the-envelope feasibility of IHBs with respect to overhead, we consider the magnitude of IHB traffic using reasonable assumptions over the expected number of participants, data rate, and receiver size.

Let the IHB observation point monitor a prefix with mask m (i.e., for a single IPv4 host $m = 32$). The probability of a single IHB participant sending a heartbeat that arrives at this observation point is then: $p = \frac{1}{2^m}$.

Assume that there are n hosts participating in IHB and sending IHB packets. For simplicity, assume that each host sends a single IHB in each epoch, i.e., they all send at the same rate. Then, the expected number of IHB packets arriving at the observation point in a single epoch is: $\frac{n}{2^m}$.

Next, assume that each source sends heartbeats to random destinations at a rate of r packets per second. Then, the expected arrival rate of IHB packets is: $a = \frac{nr}{2^m}$.

Assume that one-quarter of the IPv4 Internet addresses participate in IHB, i.e., $n = 2^{32-2} \cdot 5$. If we further assume a relatively low per-host IHB rate of $r = \frac{1}{8}pps$, we can estimate the expected traffic load on the observation point due to heartbeat traffic. For instance, at the two extremes of a single end host versus a network telescope:

- End-host ($m = 32$): $a = \frac{2^{-3}(2^{30})}{2^{32}} = \frac{1}{32}pps$
- Telescope ($m = 8$): $a = \frac{2^{-3}(2^{30})}{2^8} = 2^{19} \simeq 500kpps$

Thus, given relatively conservative assumptions over IHB deployment, we observe that a single host receives a negligible rate of heartbeat traffic, while a large aggregation point such as a /8 telescope receives a technically realistic and reasonable half-million IHB packets per second.

5.2 Security and Privacy

A consequence of increasing the visibility of hosts on the network is the potential for this information to be used in un-

⁴Here, the choice of transport protocol (§3.1) is important so that heartbeats are classified in the same way as normal traffic.

⁵With NATs this is $\ll 0.25$ of devices connecting to the Internet.

scrupulous ways. For instance, a heartbeat provides an explicit indication of a remote node’s liveness at a given instant in time, thereby providing attackers a potential target. We argue, however, that heartbeats do not enable a new attack vector, as adversaries are already capable of high-rate, exhaustive vulnerability scanning [18] and make extensive use of available hitlists [19, 30]. In practice, protecting end hosts from attacks is an issue orthogonal to liveness. Nonetheless, networks that wish to remain outwardly “dark” can easily maintain this particular security posture as IHB packets are designed to be easily identified so that their transmission and reception can be blocked as required.

Finally, heartbeats raise potential concerns over tracking and privacy. We first note that heartbeats are designed to illuminate the network, and there is no identifier that persists across networks (as might be required to facilitate tracking). And because heartbeats are periodic, they provide no explicit indication of user or host activity. While it may be possible to discern when a particular host is powered on or off, this information is again readily available via other methods, e.g., [38]. Indeed, web cookies, software updates, and other chatty protocols leak significantly more private information than IHB [1]. As such, we believe the additional security burden imposed by heartbeats to be minimal and manageable, especially in relation to their potential benefit.

5.3 Deployment and Incentives

IHBs help support global measurement and promote a better understanding of the network, and we sketched several motivating examples of how they might be leveraged. Here we envision possible incentives and paths to deployment.

DNS servers: As an initial step toward global deployment, we target DNS servers as ideal candidates to source IHBs for several reasons. First, DNS roots, authorities, and public resolvers are well-known infrastructure that is globally distributed, continually alive, and well-connected. Second, users depend on these servers as critical infrastructure. Thus, both users and providers have a vested interest in understanding, optimizing, and debugging the availability and performance of DNS connectivity.

End-users: Second, we believe IHBs can provide direct benefit to participating users as described in §4.2. While the benefit increases in proportion to the number of participants for IHBs, deployment can be bootstrapped with DNS servers, while end-users can benefit from IHBs immediately as deployment progresses. We envision IHB support within home routers and CPE to be critical for widespread adoption and plan to implement a prototype that can run on OpenWRT as a first step toward understanding how users can benefit.

5.4 IPv6

Heartbeats may be especially important in IPv6 where the size of the 128-bit address space poses unique measurement obstacles. For instance, whereas exhaustive vulnerability, census, and topology scanning, e.g., [18, 6], are infeasible in IPv6, an IPv6 IHB can naturally illuminate active hosts, net-

works, and paths. However, the sparsity of the IPv6 address space implies that choosing the heartbeat target (destination IPv6 address) at random will rarely produce an active host, much less a routed network.

With only 0.002% of the IPv6 address space advertised currently [24], only approximately one in every 50K random heartbeats will be directed toward an advertised IPv6 prefix. While randomly destined IPv6 heartbeats will be observed at darknets, the probability of reaching an active IPv6 host is vanishingly small (as small as $O(2^{-64})$ in the case of privacy preserving addresses [32]). We therefore advocate for a reserved /64 destination address suffix for IHB. In this way, network borders and telescopes can readily identify IPv6 IHB traffic, or special end-network routing may be installed for IHBs. Further, it may be possible to develop mechanisms that allow all IPv6 IHB nodes on a network segment to receive the heartbeats, for instance via a special MAC address mapping or rewriting IHB packets into link-local IPv6 multicast.

Further enhancements may be possible to bias IPv6 IHBs to active and routed portions of the address space. For instance, we observe that received heartbeats can be used to discover and learn the active address space. For example, the /64 network corresponding to the source address of received heartbeats is certain to be routed, and clustering of contiguous /64s can produce larger prefixes. IPv6 hosts participating in the IHB can bias their probing to these learned blocks to better utilize the probing budget. While this learning process might seem to require significant time (and wasted probing), we note that the control plane of routers participating in IHB have direct and accurate knowledge of the routed IPv6 address space, and can effectively act as seeds to bootstrap the learning process.

6. FUTURE WORK

Significant future work remains to realizing the IHB vision, and initial architectural choices may prove important. For instance, the current design requires a non-trivial number of IHBs before every node has touched every other node. Instead, a possible alternative is to coordinate heartbeats among participating nodes on a network segment—e.g., via a local gossip mechanism. In this way, nodes could divvy up the random permutation to minimize coverage time.

Unlike more radical network architecture proposals, implementing and experimenting with IHBs is readily possible, and we have begun just this. While IHBs could be placed into the network stack of operating systems, our approach is to develop a user-space program, `heartbeatd`, that implements IHB. We plan a small-scale deployment to perform long-term continual heartbeats. Simultaneously, we plan to explore the real-world inferences possible at a variety of observation points, including at individual nodes, a network border, CPE, and on a darknet.

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