Subnet Deduplication for Monero Node Peer Selection

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Abstract

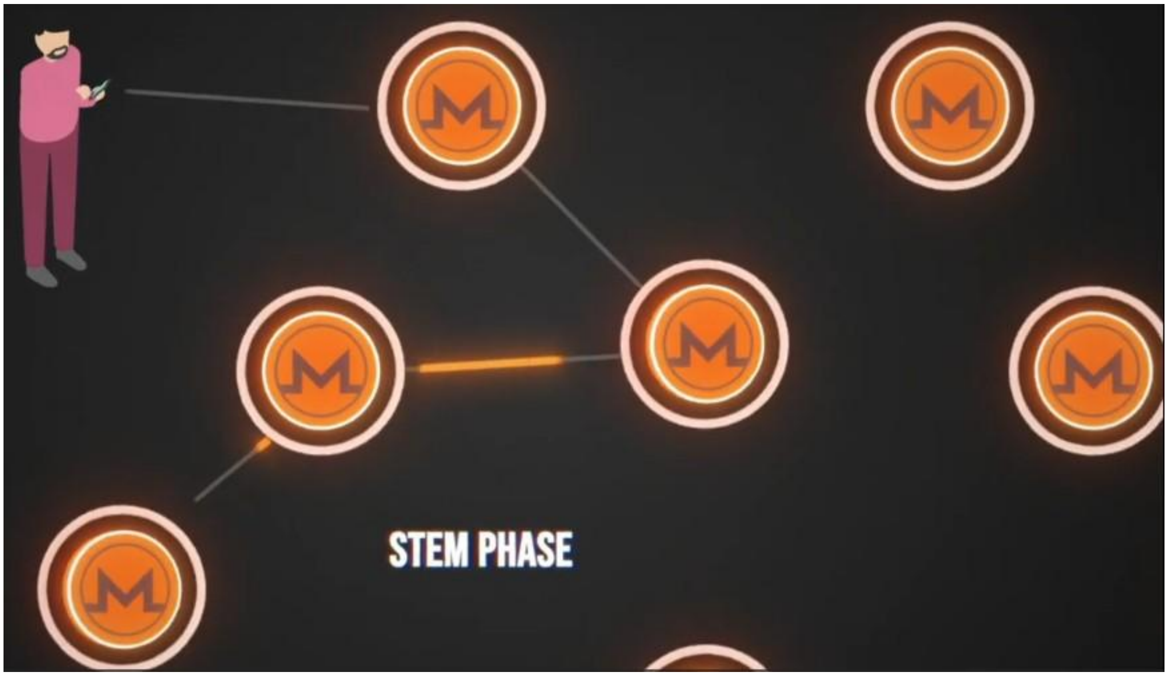
Spying adversaries can set up nodes on the Monero network to try to guess the IP address origin of a Monero transaction. A larger number of spy nodes increases the accuracy of the guesses. Adversaries can take advantage of bulk pricing on leasing subnets, which are contiguous blocks of IP addresses. This research note analyzes the effectiveness of a subnet deduplication algorithm for peer node selection. The effectiveness of the proposed algorithm against a real spy node adversary is simulated. The share of an honest node's connections that are spy nodes is reduced to 2.5 percent, compared to 33.0 percent when using the status quo peer selection algorithm. Then a game is analyzed where an adversary is free to choose its IP address leasing strategy. The subnet deduplication algorithm is more effective against the agile spy adversary when the price premium of leasing subnet-distinct IP addresses is greater than the concentration of honest nodes in subnets. Given current network conditions, the price premium must be 38 percent or greater.

1 Statement of the problem

Spy nodes operating on the Monero network are a theoretical and practical threat to user privacy. The Dandelion++ protocol helps prevent spy nodes from determining the true IP address origin of Monero transactions, but too many spy nodes can reduce the effectiveness of Dandelion++ [Fanti et al., 2018]. Since honest nodes and spy nodes alike do not require permission to join the network, the only known reliable way to limit the number of spy nodes is to impose an economic cost on the spy node operator.

One cost that spy node operators must pay is leasing IP addresses. Spy node operators can and do get bulk discounts by leasing contiguous ranges of IP addresses, called "subnets". The purpose of this research note is to analyze a countermeasure against an adversary's bulk leasing strategy. The countermeasure is simple: instead of randomly selecting peer connections from the initial candidate IP address list where spy nodes have strategically overrepresented themselves, first eliminate duplicate IP addresses in the same subnet and then select randomly from the deduplicated candidate peer list.

Figure 1: Dandelion++ stem phase illustration (courtesy of Vosto Emisio https://youtu.be/hM6TF3co7lI)



2 Background

Dandelion++, implemented in Monero in 2020, is a transaction relay protocol that reduces the probability that spy nodes will be able to guess the true IP address origin of a Monero transaction. Dandelion++ is much better than basic transaction relay methods used before, but it cannot completely defeat spy nodes. The share, p, of an honest node's outbound connections that are made to spy nodes determines the honest node's privacy risk at any given time. Higher p means greater privacy risk.

The "outbound" qualifier in "outbound connections" is important. An outbound connection from Alice's node is a connection that Alice initiates to a peer of her choosing. Alice's inbound connections are connection that other nodes initiate. In the stem phase of Dandelion++, which is the privacy-sensitive phase, transactions are relayed only to an outbound connection. Therefore, the effectiveness of Dandelion++ depends on the honest nodes' probability of selecting spy nodes as outbound connections.

The objective of the adversary is to increase the probability that honest nodes connect to the spy nodes. They can do this by routing traffic from leased IP addresses to their spy nodes. Honest nodes routinely share the IP addresses of nodes with each other. Since the Monero network is permissionless, spy nodes can simply share their IP addresses with a few honest nodes. Then the spy node IP addresses propagate throughout the network as honest nodes share peer IP addresses with each other. See [Cao et al., 2020] for more information on peer list propagation. Honest nodes randomly select from their peer candidate list when they drop old outbound connections and create new ones.

A subnet is a grouping of IP addresses. For example, a subnet with 256 IP addresses can be defined by setting the first three numbers in dot-decimal notation to the same value, then having a distinct number in the final position. Such a subnet could be all IP addresses between `91.198.115.0` and `91.198.115.255`. This is called a `/24` subnet because the first 24 bits of the IP address are fixed, and the rest are allowed to vary. Another subnet that we will discuss is the `/16` subnet, which follows a pattern of `x.x.any.any`. Despite 16 being a smaller number than 24, a `/16` subnet is much larger than a `/24` subnet, constituting 65,536 possible IP addresses instead of 256.

There are only about 4 billion possible IP addresses in the usual IPv4 format. IPv6 addresses, which allow about 3.4×10^{38} possible addresses, are disabled by default in the Monero node software exactly because it would be too easy for an adversary to set up thousands of IPv6 spy nodes cheaply.[1] Where there is scarcity and demand, there is a market and therefore a price. The limited IPv4 addresses are controlled by governments, telecommunications companies, universities, and similar entities. Some of these entities lease IP addresses on the open market. When leasing in bulk, IP addresses are usually grouped into subnets. Some brokers and lessors quote 118 to 250 USD per `/24` subnet per month, which works out to 0.46 to 0.98 USD per IP address per month.[2]

Evidence uncovered by Monero developer boog900 suggests that a spy node network is currently operating on the Monero network.[3] The spy node operator is leasing a combination of whole `/24` subnets and individual IP addresses. As a temporary measure, the Monero Research Lab has recommended that honest Monero node operators prevent connections to the suspected spy node IP addresses by enabling a `--ban-list` option on their nodes.[4] Enabling a ban list:

1. Requires node operators to trust the judgment and honesty of Monero's developers and researchers,
2. Requires updating the IP address list if the adversary changes the IP addresses it is leasing, and
3. Does not work against an adversary who deploys spy nodes that are harder to distinguish from honest nodes.

Therefore, a more universal solution is desired. Subnet deduplication can counteract the adversary's bulk discount on leasing whole subnets. First we will analyze the effect of subnet deduplication on the effectiveness of the actual spy nodes currently deployed on the Monero network. Then we will determine under what conditions subnet deduplication is more effective than the status quo peer selection algorithm when an adversary has free choice of whether to lease subnets or subnet-distinct IP addresses.

[1] See https://libera.monerologs.net/monero/20230404#c230903-c230904

[2] See https://www.ipxo.com/lease-ips/, , https://www.logicweb.com/bulk-ip-address-leasing/, and https://www.forked.net/ip-address-leasing/

[3] https://github.com/monero-project/research-lab/issues/126

[4] See https://github.com/monero-project/meta/issues/1124

3 Simulated effect of subnet deduplication on current spy node effectiveness

Monero's status quo peer selection algorithm does have one existing countermeasure against spy node subnets. If Alice's node is already connected to an IP address within a specific `/16` subnet, then Alice's node will not connect to another node in that subnet.[5] When an adversary leases many `/24` subnets that are in distinct `/16` subnets, this countermeasure is not very effective. Note that the Tor protocol requires that no two nodes in its three-node circuit can be in the same `/16` subnet [Rochet et al., 2020].

The proposed subnet deduplication peer selection algorithm keeps the original rule about not selecting a peer that is in a `/16` subnet that Alice is already connected to. In addition, it eliminates from the peer candidate list all but one IP address in each `/16` subnet. This form of the subnet deduplication algorithm is the most aggressive. Less aggressive forms could deduplicate at a smaller subnet level or keep more than one IP address in each subnet after deduplication.

To compare the effectiveness of spy nodes against the status quo algorithm and the subnet deduplication algorithm, we must collect a list of spy nodes, honest nodes, and their subnets. A list of IP addresses accepting inbound connections for the Monero protocol can be obtained easily by a Monero network scan.[6] First, the scanner contacts the Monero seed nodes to get an initial list of nodes on the network. Then the scanner contacts all the nodes on the initial list, requesting their own lists of nodes' IP addresses. The scanner iterates through the accumulated list until all contactable nodes have been contacted. These nodes can be classified into their subnets and cross-referenced against the list of suspected spy nodes.

Figure 2 plots a treemap of honest nodes and spy nodes that accept inbound connections, based on a network scan performed on February 11, 2025. Each of the 4,433 small colored rectangles represents one node's IP address. Nodes in the same `/16` subnet are grouped inside black-lined perimeters and are labeled with white text where possible. Nodes in the same /24 subnet are grouped inside yellow-lined perimeters. The share of the plot area that is red is approximately the share of spy nodes on the network. Along the left side and bottom of the plot, we observe six `/24` subnets within distinct `/16` subnets that are entirely occupied by spy nodes. Smaller numbers of spy nodes are scattered among `/16` subnets that they share with some honest nodes, yet are in distinct `/24` subnets (observe the yellow lines). These subnets are likely owned by server providers used by honest nodes and spy nodes alike. There are only two spy nodes alone in their own `/16` subnets, but the majority of honest nodes are alone in their own `/16` subnet.

[5] https://github.com/monero-project/monero/blob/84df77404e8bcbe1cf409f64c81e4e4f9c84885b/src/p2p/net_node.inl#L1588
[6] https://gist.github.com/Boog900/5e9fe91197fbbf5f5214df77de0c8cd8

Figure 2: Subnet treemap of honest and spy nodes

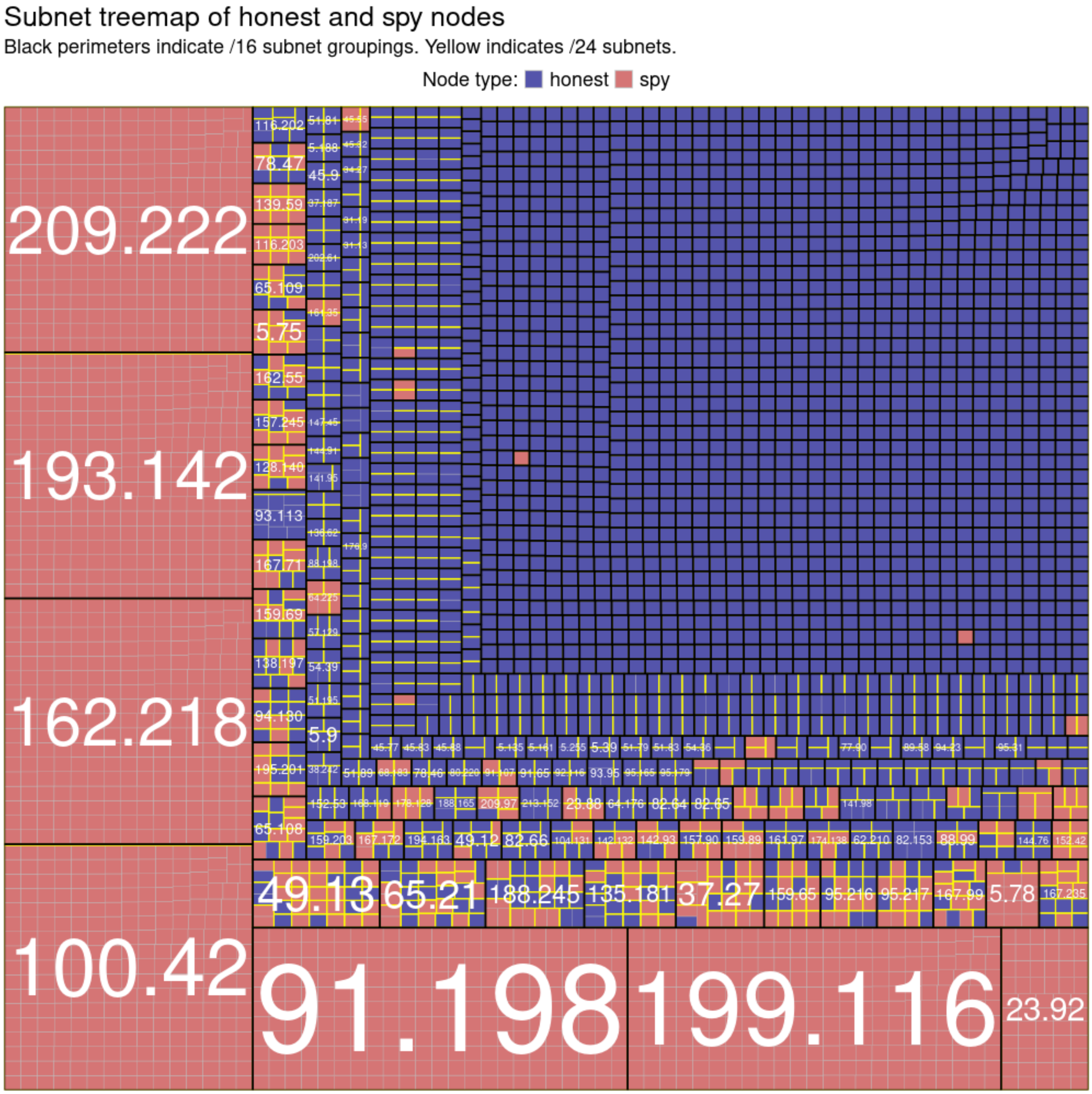
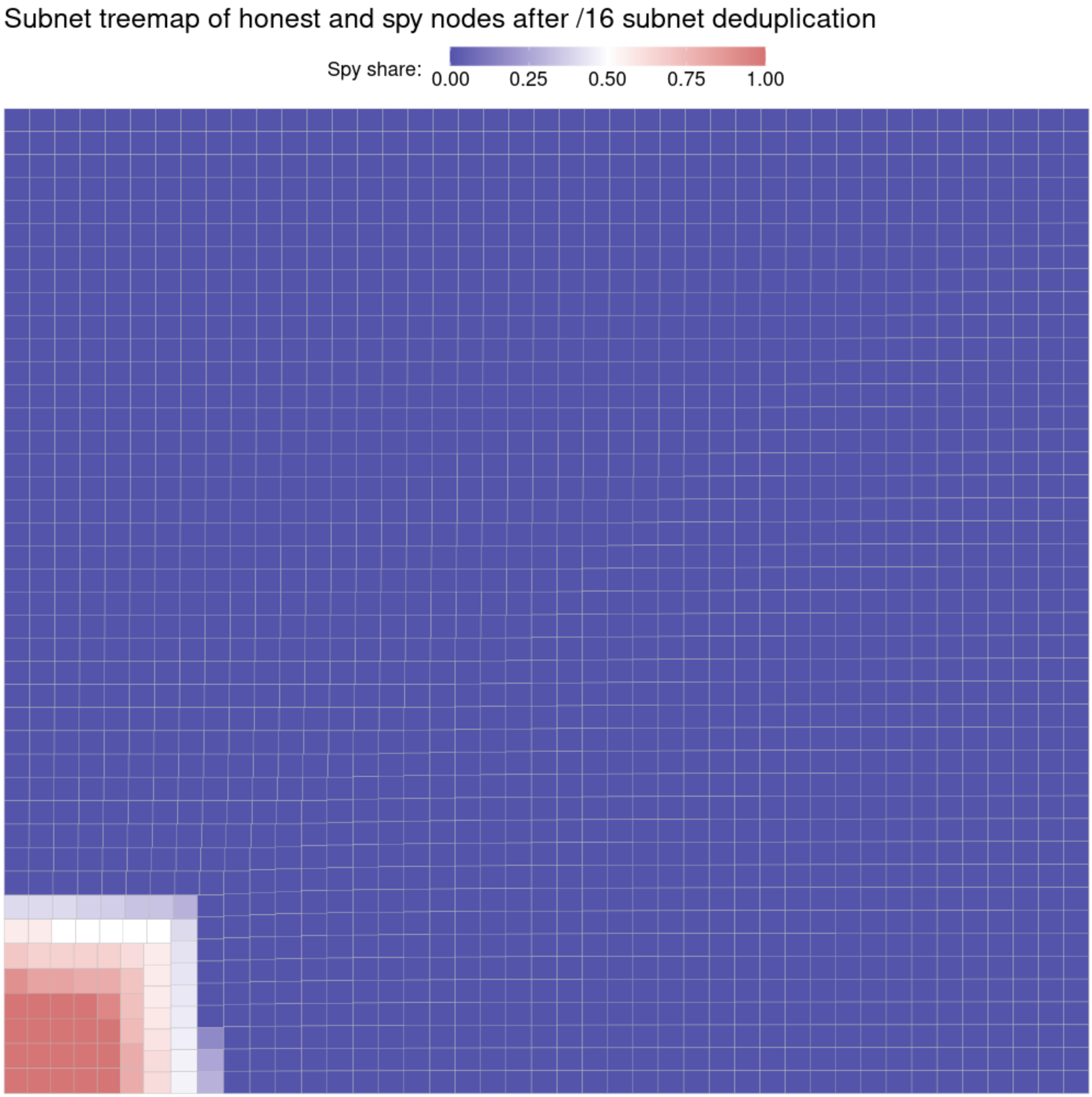


Figure 3 shows a treemap of honest nodes and spy nodes after deduplication of `/16` subnets. When a `/16` subnet contains both honest nodes and spy nodes, the rectangle's color is a mixture of blue and red proportional to the share of honest and spy nodes in the subnet. Compared to Figure 2, the area occupied by the red spy nodes is much smaller after subnet deduplication.

Figure 3: Subnet treemap of Honest and spy nodes after /16 subnet deduplication



If each node chose a single peer node, then the share of connections to spy nodes could be computed simply by dividing the total number of nodes by the number of spy nodes. However, by default nodes choose 12 outbound peers without replacement. Probability computations where elements are drawn without replacement with unequal probability are known to be much more complicated than in problems where elements are drawn with replacement with unequal probability [Tillé, 2023]. The computation is further complicated by the the status quo rule to not select a peer in a `/16` subnet when already connected to a peer in that `/16` subnet.

I wrote a Monte Carlo simulation that imitates the status quo and subnet deduplication peer selection algorithms, using the data from the network scan as its basis. First, the 12 outbound peer slots are filled sequentially using the respective peer selection algorithm. Then, peer "churn" is simulated 100 times. A churn occurs when one peer is randomly dropped and a new one chosen, using the peer selection rules. This simulation is done 10,000 times to estimate the real share of a typical nodes's outbound peer connections that would be composed of spy nodes. Note that the Monte Carlo simulation ignores the fact that nodes' `white_list` and `gray_list` are limited to 1,000 and 5,000 IP addresses, respectively. See [Cao et al., 2020] for more details about Monero's graylist housekeeping.

The results of the Monte Carlo simulation are as follows. When the status quo peer selection algorithm is used, the share of connections to spy nodes is 33.0 percent. When the subnet deduplication peer selection algorithm is used, the share of connections to spy nodes is 2.5 percent.

4 Protocol-adversary interaction as a game

Behavior is not static. When the actions of one agent change, other agents may change their behavior, too. Therefore, we must go beyond analyzing the effectiveness of subnet deduplication against a specific adversary's current behavior. If the Monero protocol switches to subnet deduplication, could privacy actually worsen? Can the cure be worse than the disease? We will set up a simple game theory model and compute under what conditions it is better to use the subnet deduplication peer selection strategy. The theoretical result of this section is that the choice of the honest node's strategy depends on the price difference between bulk and individual IP address leasing, compared to the concentration of honest nodes within subnets.

We make the following assumptions:

1. The privacy impact of spy nodes is equal to the probability of connecting to a spy node in a single draw, with replacement. This ignores the more complicated computations of drawing without replacement discussed in the previous section.

2. Conditional on the pricing structure (i.e. bulk subnet or subnet-distinct IP addresses), costs are a linear function of price. In other words, if w is the price and x is the number of IP addresses leased, then the cost is $w \cdot x$. This assumption may not be realistic if the adversary exhausts low-cost IP address providers when leasing a large number of IP addresses, and then must resort to high-cost IP address providers.

3. The adversary is assumed to either lease only subnets or only subnet-distinct IP addresses, i.e. no hybrid strategies. This assumption could be relaxed in further work.

There are two players, an honest node and a spying adversary. They each can play two possible strategies. The honest node can use the status quo peer selection algorithm or the subnet deduplication peer selection

Table 1: 2x2 normal-form game

		Adversary	
		Lease whole subnets	Lease subnet-distinct IP addresses
Honest node	Status quo	$-p_{s,s}, \quad p_{s,s}$	$-p_{s,d}, \quad p_{s,d}$
	Subnet deduplication	$-p_{d,s}, \quad p_{d,s}$	$-p_{d,d}, \quad p_{d,d}$

algorithm. The adversary can lease whole `/24` subnets at a bulk price discount or lease individual subnet-distinct IP addresses. The game is assumed to be zero-sum. The payoff function for the adversary is the probability that a single peer chosen by the honest node is a spy node. The payoff function for the honest node is the negative of that probability.

Define these probabilities that an honest node selects a spy node peer:

$p_{s,s}$ when the honest node uses the status quo peer selection algorithm and the adversary leases whole subnets,

$p_{d,s}$ when the honest node uses the subnet deduplication peer selection algorithm and the adversary leases whole subnets,

$p_{s,d}$ when the honest node uses the status quo peer selection algorithm and the adversary leases subnet-distinct IP addresses, and

$p_{d,d}$ when the honest node uses the subnet deduplication peer selection algorithm and the adversary leases subnet-distinct IP addresses.

Table 1 shows the normal-form game. The left side of each cell is the honest node's payoff. The right side is the adversary's payoff.

We want to know under what conditions will the honest node have more privacy with a subnet deduplication peer selection algorithm instead of the status quo peer selection algorithm. We assume that the adversary uses the "lease whole subnets" strategy when the honest node uses the status quo algorithm and the adversary uses the "lease subnet-distinct IP addresses" strategy when the honest node uses the subnet deduplication algorithm. Therefore, we want to know under what conditions $p_{s,s} > p_{d,d}$.

Let

h_s be the total number of honest nodes that accept inbound connections, including nodes in the same subnet,

b be the budget of adversary,

a be number of IP addresses leased by adversary, and

w_s be the price per IP address when leasing whole subnets. (If the price to lease a subnet is 150 USD, then the price per IP address is $150/254 = 0.59$ USD because there are 254 usable IP addresses in a `/24` subnet.)

When using the status quo peer selection algorithm, the probability that an honest node selects an adversary's IP address as a peer is simply the share of nodes operated by the adversary:

$p_{s,s} = \dfrac{a}{h_s + a}$

How many adversary nodes exist? The adversary exhausts its budget, so $a = b/w_s$. Now we have the probability that an honest node selects an adversary's IP address as a peer in terms of the adversary's budget, the price per leased IP address, and the number of honest nodes:

$p_{s,s} = \dfrac{b/w_s}{h_s + b/w_s}$

Multiplying through by w_s gets us a simpler expression:

$$p_{s,s} = \frac{b}{w_s h_s + b} \tag{1}$$

$p_{s,s}$ denotes the probability that an honest node selects an adversary's IP address when honest nodes are following the status quo peer selection algorithm and the adversary is leasing whole subnets. Next, we will compute $p_{d,d}$, the probability that an honest node selects an adversary's IP address when honest nodes are following a subnet deduplication peer selection algorithm and the adversary is leasing IP addresses only in distinct subnets.

Let

h_d be the number of distinct subnets with at least one honest node and

w_d be the price to lease one subnet-distinct IP address.

By a similar logic as in the $p_{s,s}$ case,

$$p_{d,d} = \frac{b}{w_d h_d + b} \tag{2}$$

Comparing (1) and (2), it is easy to see that $p_{s,s} > p_{d,d}$ if and only if $w_s h_s < w_d h_d$. Rearranging, we have this condition:

$$\frac{w_d}{w_s} > \frac{h_s}{h_d} \tag{3}$$

This inequality says that subnet deduplication is a better strategy for the honest node if the price premium of leasing subnet-distinct IP addresses is more than the ratio of the total number of honest nodes to the number of distinct subnets with at least one honest node. Note that this condition does not depend on the adversary's budget.

At any given moment, h_s/h_d can be computed by performing a network scan, assuming we can determine which nodes are honest. Using the network scan and list of suspected spy nodes from the previous section, we have $h_s/h_d = 1.38$. That means that the subnet deduplication algorithm is better than the status quo if the price premium to lease subnet-distinct IP addreses is 38 percent or greater. Of course, the subnet concentration of honest nodes can change over time.

References

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