

An empirical study of availability and reliability properties of the Bitcoin Lightning Network

Finnegan Waugh
University of Sydney

Ralph Holz
University of Twente & University of Sydney

Abstract—The Bitcoin Lightning network is a mechanism to enable fast and inexpensive off-chain Bitcoin transactions using peer-to-peer (P2P) channels between nodes that can also be composed into a routing path. Although the resulting possible channel graphs are well-studied, there is no empirical data on the network’s reliability in terms of being able to successfully route payments at a given moment in time. In this paper we address this gap and investigate two forms of availability that are a necessary ingredient to achieve such reliability. We first study the Lightning network’s ability to route payments of various sizes to nearly every participating node, over most available channels. We establish an inverse relationship between payment volume and success rate and show that at best only about a third of destination nodes can be successfully reached. The routing is hampered by a number of possible errors, both transient and permanent. We then study the availability of nodes in the network longitudinally and determine how long-lived they are. Churn in the network is actually low, and a considerable number of nodes are hosted on cloud providers. By testing node liveness, we find that the propagated network information is relatively often stale, however, both for IP addresses and Tor onion addresses. We provide recommendations how the Lightning network can be improved, including considerations which trade-offs between privacy and decentralization on the one hand and reliability on the other hand should at least be reconsidered by the community developing the Lightning network.

I. INTRODUCTION

More than ten years after the creation of the first public blockchain, the number of transactions that Bitcoin can process is orders of magnitude below that of classic payment systems operated by banks and credit card providers. Regulatory issues aside, this is one of the main factors that have held Bitcoin back from becoming the globally accepted, decentralized cryptocurrency that its developers meant it to be. A number of solutions have been proposed to overcome Bitcoin’s performance issues. Among the most interesting ones are those that focus on bypassing the blockchain for most transactions and use it as an anchor to keep track only of the result balance of an entire set of off-chain transactions. Collectively, these approaches are often known as *Payment Channel Networks (PCNs)*.

The Lightning Network is such a technology for Bitcoin. It defines peer-to-peer (P2P) payment channels to facilitate smaller transactions between two partnering blockchain participants. Only the sum of all P2P transactions is written out to the blockchain. By chaining channels together, one can also ‘route’ payments to participants to which no direct network connection exists. The fees that channel operators charge are

very low compared to Bitcoin’s current fees. The design goals of Lightning Network emphasize fast payments, with latencies on the order of a fraction of a second. By keeping most transactions off-chain, the Lightning Network also hopes to achieve better privacy for users and a drastic reduction of required storage space for the blockchain. However, there is a tension between the design goals of *reliability* and *decentralization*. To be acceptable to users as a common form of payment, the Lightning Network must offer a high degree of reliability in the sense of *payments reaching their destination*. An expressive goal of the Lightning Network is to maintain a high degree of decentralization [1]. As the Lightning Network is set up as P2P network, where nodes are free to come and leave any time, this means that *availability*, in different forms, is a prerequisite for the network’s reliable functioning.

In this paper, we focus on two related forms of availability that are a necessary condition for the latter. The first is *availability of channels at the time of payment*, i.e., the property that (composite) payment channels must be available and capable of transporting a certain transaction volume to a payment destination. This property can be directly measured by running experiments in the network. The second form of availability that we focus on is *overall availability of nodes in the network*, in the sense that nodes must not go stale over time: they should remain in the network for appropriate periods, and they need to respond to queries such as requests to connect or establish payment channels etc. This second form of availability is, in fact, a constituent of the first form; it can also be described as a function of network composition. However, as we will see, it can be measured only for a part of the network due to the Lightning Network’s design. This means that it is important to measure both forms of availability as data for both allows us to more accurately gauge the Lightning Network’s overall chances of routing payments successfully. We acknowledge that further factors such as security against attack, safety of operation such as recovering from errors, etc. are all further important properties to fully understand the Lightning Network. They are even harder to measure at scale, however, and for this paper, we consider them out of scope.

The Lightning Network network is now about four years old. Previous work has investigated the properties of the graph established by payment channels. However, these studies are based on *summary snapshots* of channel information that is propagated in the network over a longer period of time. In

this sense, such studies consider a best-case picture, under the assumption that all channels and responsible nodes are actually really available. To the best of our knowledge, there is no existing work that investigates the actual availability properties of channels at the time a payment is attempted, nor does data on the overall availability of network nodes exist. In this work, we aim to close this gap. Our main contributions are as follows:

a) Availability of payment routes: We determine the Lightning Network’s ability to route payments of various, plausible sizes to the intended destination. We construct a way to probe the Lightning network for its ability to route payments of different volumes. Our probing covers almost the entire network. Our results establish a strong link between success rate and payment volume. We identify both transient errors (insufficiently funded channels) and intransient errors (such as offline nodes) as the primary reasons for failing payments. We find that only small payments have a reasonable chance to be successful and that only a relatively small number of nodes, and hence payment destinations, can actually be reached.

b) Availability of the network substrate: We investigate the directly observable part of the Lightning network layer, *i.e.*, those nodes that publish their network addresses. While the network is well distributed over many Autonomous Systems, many nodes are also run in the cloud or hosted by commercial providers. We test the liveness of nodes and determine network churn, which is a crucial factor for availability. While the latter is relatively low, we find that propagated network information is often stale, despite protocol mechanisms to eliminate it. This contributes to overall poorer performance.

c) Recommendations: We conclude with a set of recommendations how the Lightning Network can be improved and potentially developed into a viable payment option. While some changes are mere technical extensions, others require to rethink the degree of privacy desired for the network and the level of centralization that one wants to accept.

The remainder of this paper is organized as follows. In the next section, we provide the relevant background to understand how the Lightning Network works and is set up. We follow this up with a discussion of related work in Section III. In Section IV, we describe our choice of measurement methods with respect to determining availability and reliability. We present our results in Section V and give key take-aways. We discuss potential improvements, including a rethinking of privacy and centralization aspects, in Section VI.

II. BACKGROUND

The Lightning network is a representative in the class of Payment Channel Networks (PCNs), which are one possible answer to the scalability issues inherent to many blockchain designs. Bano *et al.* provide a good introduction to blockchain and the particular problem space of accelerating payments in [2]. Several different approaches to PCNs are known; Gudgeon *et al.* give an overview in [3].

a) Payment channel networks: In PCNs, a large number of transactions between a limited number of nodes can

be carried out ‘off-chain’, without sending the transactions to the blockchain. Conventionally, the blockchain consensus protocol is responsible for deciding which transactions are considered correct and committed to the blockchain; herein lies an important bottleneck. In a PCN, the consensus protocol is typically only used to anchor the faithful creation and deletion of *payment channels* between nodes. At the time of writing, only Bitcoin’s Lightning Network is operated on a main blockchain by default. In the following, we limit ourselves to the Lightning Network.

b) Difference to blockchain network: Since PCNs operate on top of a blockchain, they are sometimes called Layer 2 solutions, built on top of the blockchain consensus protocol (Layer 1), which itself runs over Layer 0, which is the protocol that organizes the blockchain P2P network. We do not use the layer terminology here to avoid confusion: two distinct protocol layers can also be identified for the Lightning Network itself. One is responsible for the creation and management of a P2P network of participating Lightning nodes, and one is used to manage payment channels and forward payments. Consequently, the substrate of the Lightning Network is a P2P network that is distinct from the Bitcoin network that maintains the blockchain: every Lightning Network node runs a Bitcoin client as well, but the inverse is not true. The wallet used for the Bitcoin client is also different from that for the Lightning client. The network organization happens separately, but in a similar way, using a discovery protocol based on a gossiping mechanism. Nodes in the Lightning Network have identifiers that are used in the Lightning protocol. These are propagated between participating nodes. However, the *network* addresses, *i.e.*, IP and port or alternatively Tor onion addresses, are *not* necessarily gossiped. A client participating in the Lightning Network learns only the network addresses of nodes that choose to reveal them. In the popular *c-lightning* implementation, for instance, operators must manually enable this. This is ostensibly done for privacy reasons. However, it means that many nodes that are potential destinations are only known via their identifier, and they can only be reached via the node(s) that they choose to connect to themselves. All other nodes in the network must hence find a *route* via the latter nodes to send them a payment.

c) Payment channels: A node that is connected to another Lightning node is expected to open a payment channel. In essence, this is an agreement between the two nodes to commit a certain amount of Bitcoin to the operation of this channel. This initial commitment (the funding transaction) is anchored in the Bitcoin blockchain with a special transaction, where the funds are stored in a so-called multisignature address that is controlled by both parties. Each party has a balance in the channel, and both balances together make up the *channel capacity*. The key idea is now that both parties can send each other any number of transactions (so-called commitment transactions) and update their respective view of the balances, with newer commitment transactions invalidating previous ones. As long as both parties behave honestly, there is no need to involve the blockchain consensus

protocol. This only needs to happen when the channel is closed again: the peers are reimbursed and the final balances are written out to the blockchain. A channel can be closed unilaterally or bilaterally. Commitment transactions are still normal Bitcoin transactions; the obvious risk to address is the misbehavior of a peer attempting to steal funds. Lightning does this with a relatively complex mechanism that ensures that only the most recent commitment transaction is ever broadcast to the blockchain *and* accepted. Each peer holds cryptographic proof that can be used against the other side in case this condition is violated, *i.e.*, one party sent an older commitment transaction to the blockchain. In such a case, the funds of the misbehaving side are awarded to the victim of the attempted fraud. The exact mechanics are described in a whitepaper [1]; implementation details are given in an RFC-style document [4].

d) Sending payments: Payments in Lightning are fundamentally different from Bitcoin transactions. A receiver must create a so-called *invoice* and make it available to the sender. With the invoice, the sender can try to make the payment. Channels may be chained to allow sending payments to any destination to which a valid route (chain of channels) can be determined. This is achieved with so-called Hashed Timelock Contracts. The idea here is that the sender determines a path over a number of channels (source routing). Each node on this path is only aware of predecessor (incoming payment) and successor (outgoing payment); this is the same principle as in the Tor network (onion routing). To set up the entire routed payment, the node that is the final destination of a payment generates a secret, random value and sends it as a hash value to the source of the payment as part of the invoice. A chain of payments along the channels is created based on this hash value. Once the destination redeems the final transaction, the preimage of the hash is revealed in such a way that, in reverse, every node on the path can also redeem the funds they used to make the payment possible. The invoice mechanism provides a very useful way for us to probe the network: by generating invalid invoices, we can determine the validity and capacity of routes without a need to make actual payments.

e) Routing: To allow nodes to identify paths through the network, the Lightning Network broadcasts every known channel between nodes. This only needs to involve the channel identifiers and the identifiers (public keys) of source and destination nodes, not their network addresses. The balances of channels are not broadcast for privacy reasons. Consequently, it is entirely possible that a routed payment fails because one of the channels in the chain does not have the necessary capacity or the sender is currently insufficiently funded as the channel has already executed too many outgoing transactions. This is signalled back to the source with an error code once the payment is tried. We make use of this behavior when probing the network: it allows us to test which transaction volumes are supported by the network and how many nodes can be reached in relation to the transaction volume.

III. RELATED WORK

While the Bitcoin network and a few other blockchain networks have been the subject of measurement studies before (e.g., [5], [6], [7]), PCNs have received less attention. Several websites exist that visualize the information that can be obtained from running a Lightning node and offer so-called ‘public snapshots’ (e.g., 1ml.com, Indexplorer.com). Such data is used in a number of publications, e.g., [8], [9], [10], [11]. A drawback of this kind of data source is that it is unclear whether outdated information (inactive nodes) has been removed; it is also unknown from which or how many vantage point(s), and at which time, the data was raised.

To the best of our knowledge, there is no previous academic publication that analyzes the composition of the Lightning P2P network or identifies the Lightning Network’s efficacy in terms of routing. The work that is probably closest to ours is published by Decker in the Blockstream company blog [12]. The author describes a reachability experiment that also uses the *probe* module of the *c-lightning* implementation. However, the probing is limited to one-hop reachability tests. The author identifies just 829 nodes with publicly announced network addresses. At the time of measurement (November 2019), 27.4k channels were known, with a total capacity of just 827 BTC. Disregarding nodes without active channels, Decker identifies 65% of nodes as reachable, *i.e.*, responsive to the probe and a working destination for payments. He also briefly investigates transaction latency and stuck payments. Unlike our work, there is no systematic attempt to explore the capability of the network to transport payments of various volumes nor reachability over routes consisting of several channels.

Most related work studies only the channel graph that is propagated in the network, but not actual availability by measurement. The graph’s robustness properties have been investigated several times, including its small-world and scale-free properties. Martinazzi and Flori study the graph for the first year of the Lightning Network’s existence [8], relying on public snapshots and determining graph properties, especially scale-freeness. Seres *et al.* [11] use public snapshots from January 2019. At the time, the channel graph consisted of 16.6k channels; the Lightning Network had a capacity of 540 BTC. Naturally emerging scale-free networks are typically very robust to random failure but not to targeted attack. The authors confirm this for Lightning as well by simulating the removal of nodes with many channels. An important conclusion is that the network needs dedicated protection against Denial-of-Service attacks where the attackers go after the most important nodes. Similar results are also presented in [13], [14], [15], with the latter concluding that the Lightning network exhibits a core-periphery structure.

Rohrer *et al.* [16] derive the channel graph from running two nodes in the network themselves and dumping the identified channels. They also establish the small-world property and the scale-freeness of the graph but bolster their result with robust statistical tests, which is an absolute requirement to

identify scale-free networks¹. The authors provide a count of vertices in the channel graph, which rose from 1.5k to 2.4k between November 2018 and February 2019. They then design an attack to make channels temporarily unavailable by creating HTLCs such that nodes on a route must wait for the time locks to expire.

Herrera-Joancomarti *et al.* [18] design an attack to determine the balances of Lightning channels, which are meant to be confidential between the endpoints to increase privacy. They show a proof-of-concept on the Bitcoin testnet that involves the repeated probing of a channel with the help of invalid payments. While the design of the probing is similar to our approach, we are not concerned with attacks in this paper. In [19], the same authors build on the above attack to temporarily lock the channel balance of targeted, central nodes, making them unavailable for the rest of the network.

Some work analyzes the economics of operating a Lightning node. Ersoy *et al.* [9] design an algorithm to maximize profit from operating a Lightning channel. They evaluate their algorithm using empirical data downloaded from 1ml.com. In [10], the authors investigate whether running a Lightning Network node is economically rational. They simulate transactions on the Lightning Network based on graph snapshots and data on transaction fees from [16]. Based on the current channel graph and some (strong) assumptions of user behavior, they answer the question in the negative.

Finally, several authors devise solutions to remove potential bottlenecks in payment routing, e.g., [20], [21]. These are not necessarily specific to the Lightning network.

IV. METHODOLOGY

We explain our methods to test the availability of payments routes and the overall node availability in the network.

A. Availability of channels payment routes

The first part of our methodology addresses the first form of availability we described in Section I. The goal is to measure systematically how many payment channels and payment routes support a payment of a given volume and how many destination nodes can be reached by routing payments through the network, over channels of various lengths.

We test channels by running a Lightning node in the cloud, specifically a DigitalOcean location in San Francisco. We refer to this node as Node A. The node has both IPv4 and IPv6 connectivity. We fund our own node with the equivalent of about US\$120 and open initial channels to well-connected nodes. We choose the two nodes that have the highest number of public open channels and do not reject our request to create a channel with sufficient funding. One node accepts our funding of the Bitcoin equivalent of US\$100; the other only accepts a funding of US\$20. At the start of our probing, one node is the source point of 867 channels; the other of 840.

c-lightning provides the ability to add user-defined plugins to extend its functionality. One such plugin is the *probe*

module, which allows a user to test a payment to another node. It achieves this by sending a payment with an invalid (random) payment hash. When the payment arrives at its destination, the recipient is unable to redeem it and returns an *Unknown Payment Details* error. This error indicates that the reachability experiment was actually successful. If the payment cannot be routed through the specified route, then a different error will be returned (see below). An advantage of this kind of probing is that it allows to test payments without actually spending Bitcoin.

We modify the probe module to support testing the availability of channels for payments of a certain volume. We do this by breadth-first search. Using the method described above, the modified plugin tests payments through as many channels as it can reach. It first tries to route a payment through the channels it has open with the initial peers. If these are successful, it attempts to route the payment through each of the channels that each of the respective peers has open, except for those channels that have already been tested. It continues in this breadth-first manner until no more channels can be reached. We cannot probe every single channel in existence: some are unreachable from our initial nodes. To test them, we would have to iteratively establish channels to (potentially many) other nodes. As there is no guarantee they would accept payments of the volumes we choose, we regard this alternative methodology as having diminishing returns. Furthermore, we note that payments may also fail due to transient reasons (see Section V-A).

We begin our experiment on 2019-11-03 and end it on 2019-11-25. For each attempted payment (reflecting a composition of channels), we make at most two payment attempts and store whether one of the two attempts was ‘successful’ or we could not recover from an error. Since each channel direction has a different balance and potentially different fees for forwarding, we probe each channel direction. As transaction volumes, we choose the Bitcoin equivalent for US\$0.01, US\$1, US\$5, US\$10, US\$50 and US\$100 at the time of the experiment’s start.

B. Availability of nodes in the P2P network

The second set of measurements addresses the second form of availability we discussed in Section I. The goal is to establish how many nodes whose network addresses are propagated through the network actually reply to attempts to contact them. This also allows us to compute churn in the network. As explained in section II, measurements of the Lightning network layer are limited to nodes that consent to the propagation of their network addresses by other peers.

1) *Input data*: We have two input data sources, which we use for different purposes. First, we have access to data raised by developers of the *c-lightning* client. The *listnodes* RPC call provides a mapping between the *node identifier* (*node ID*) and known network address. These can be any combination of IPv4, IPv6, and Tor onion addresses. The data set is split into days. For each day, it lists the node IDs and last known addresses on the day or prior. The data set covers the

¹It is a premature conclusion to call a graph scale-free based only on visual inspection of a double-log plot as many other authors did; see [17] for details.

period 2019-09-15 through 2019-11-30. In addition to node information, we also obtain the known channels (with source and destination nodes) of each day.

According to [12], stale nodes, *i.e.*, nodes with no active channels, should be purged with the client’s default settings. This view of the network would be in contrast to public visualization sites such as *1ml.com*, which do not employ this purging and consequently overestimate the network size. The specification of the Lightning Network protocol also mentions pruning stale nodes and channels explicitly. We would hence expect most nodes to be responsive. In order to test the liveness of nodes ourselves, we install a further Lightning node in the network of the University of Sydney, which we refer to as Node B. The university network has only IPv4 available. We fund a channel with 0.001 BTC, *i.e.*, about US\$ 10 at the time of the experiment. We run the node from 2020-02-18 onwards. As the node has only one channel, we note that this may mean the node receives fewer announcements via the discovery gossip protocol than nodes with many active channels (and hence connected peers). We return to this in Section V-B. We also use the *listnodes* RPC call of *c-lightning* to dump node information.

We map the IP addresses of Lightning nodes to Autonomous Systems (ASes) using *pyasn* in conjunction with Routeviews routing information at the corresponding time. We use Team Cymru’s WHOIS service (v4.whois.cymru.com) to map the AS number to the operator name and registration with a Regional Internet Registry (RIR). This gives us the name of the network hosting a node.

2) *Testing liveness*: For nodes learned with our own Lightning Node B, we use two methods to check their liveness and reachability. For *IPv4 nodes*, we use the extremely fast Internet scanner *zmap* [22] to test whether they respond on the allocated port. This scan takes place from the University of Sydney and takes only two minutes. Almost all nodes use the Lightning default port (9735); we hence limit our investigations to this port.

A significant number of nodes publish a *.onion* network address, which refers to a Tor hidden service. Such nodes are only reachable via rendezvous points using the Tor anonymization network. We deploy a Tor daemon on our server and connect via the *c-lightning* client to test their liveness.

3) *Limitations*: Only a subset of nodes publishes their network addresses. This may introduce a bias: it is conceivable, for example, that operators running the Lightning software on a public server (e.g., a VPS) are more likely to publish their network address than private users in a home. This is particularly true if they aim at making a profit by collecting fees from their channels. A similar argument holds for Tor hidden services, which should ideally also be longer-lived. We keep this limitation in mind when discussing our results.

C. Ethical considerations and reproducibility

Although it is deployed on Bitcoin’s *mainnet*, the Lightning Network network is still in a testing stage. Developers monitor the network and occasionally probe it for metrics like

reachability [12]. This monitoring is one of our data sources. Internet scans and interactions with cryptocurrency networks, which constitute another part of our methodology, have been cleared by the Human Ethics Committee of the University of Sydney. We employ several guiding principles to minimize the impact of our measurement on the Lightning Network. We refrain from attempts to include every single channel in our breadth-first search as this would imply many additional channels would have to be opened. We also limit ourselves to just two probes for payments.

We support open science and will make both our source code and our data available publicly available.

V. RESULTS

We first present our results on availability of payment routing and then the results on overall availability of nodes in the network.

A. Availability of channels

According to our data source from the *c-lightning* developers, which collected daily snapshots, between 31.4k and 31.8k channels existed between 2020-11-03 and 2020-11-25 and were not stale. Although we do not attempt a full combinatorial testing of all possible routes (see Section IV), our own probes from our initial, well-connected hop cover a significant amount of the propagated channels: 30.7k are reached by the probes. This corresponds to 49.2k channel directions. Note that we do not reach the theoretically possible 61.4k directions: many nodes have only a single channel open, and if a probe is not able to traverse the channel to a given endpoint, then it is not possible to test the reverse direction, either. While the overall number is high and seems to imply that reachability in the Lightning Network is very good in principle, the picture changes dramatically when looking at the success rate of payments.

1) *Success of payments*: According to our data from the *c-lightning* developers, between 4826 and 4950 nodes are observed during our experiment period. In our experiments, we attempt payments to a total of 4626 unique nodes, *i.e.*, we cover between 93.5%-95.9% of existing nodes. However, the success rate of attempted payments varies between 15.32% and 72.09%, depending on the payment volume. The number of nodes that we reach with a payment is also considerably lower than the number of nodes we attempt to send a payment to: just 2055. This number is the *union* of all unique nodes reached over all probes of various payment volumes (Table I). We can never reach more than roughly at third of all nodes, independent of payment volume. Note that the relatively long duration of our experiment implies that some nodes that were reachable during tests with one payment volume may be unreachable again for the next, or vice versa.

We observe a strong inverse relationship of successful payments to the volume used, which we summarize in Table I. While by far the most very small payments of US\$0.01 are successful overall (72%), we still reach only 35% of nodes overall. The numbers for successful payments drop

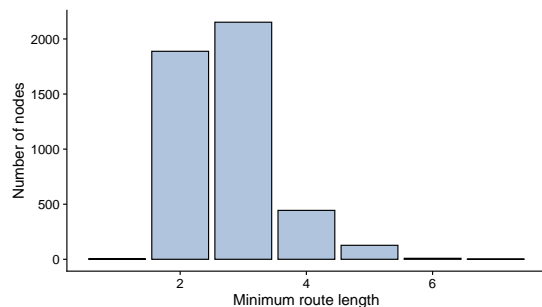


Figure 1. Minimum number of hops to reach nodes.

Table I
SUCCESS RATE FOR PAYMENTS AND *unique* NODES REACHED.

Amount (US\$)	% payments	% nodes	# nodes
0.01	71.92	35.24	1630
1	57.82	35.19	1628
5	44.06	25.66	1187
10	44.15	33.72	1560
50	30.93	9.22	459
100	17.30	4.82	223

immediately when we increase the volume to US\$ 1, however the number of reached nodes stays almost the same. Evidently, a sufficient number of payment channels are alive and functioning to enable this volume. While 35% of nodes seems to be an upper number in terms of reachability for practically useful payments, we note that some of the payment routes are longer than others, meaning that such routes imply a higher overall chance of failure. The numbers deteriorate fast with higher payment volumes. Payments of US\$ 50 and above do not reach any significant number of nodes any more. It is unclear from our observations why more nodes can be reached for US\$ 10 than for US\$ 5; however, we emphasize the high rate of transient errors in channels, which we explore below.

We also compute how many hops are needed to reach the destination. Figure 1 shows this. Even with just two outgoing channels, it is possible to reach the vast majority of nodes via two or three hops. Note that the principle of onion routing requires two hops from the source, *i.e.*, one ‘intermediate’ and one ‘exit’ node before the final hop (the destination).

2) *Reasons for failing payments:* Table II summarizes the errors we determined across all payments. The most common error was a temporary channel failure. This error is reported when a channel direction has temporarily insufficient funds available. This can be a result of previous transactions through the channel that have been locked. The error indicates the same payment may succeed through the channel at a later time. The next most common error was *Unknown Next Peer*. This indicates a hop along the intended payment route did not have a connection to the next node. Less than 1% of payments returned a channel disabled error. Other errors occurred very rarely; we attribute them to the client having slightly out of date information about some parts of the network. Payment

Table II
BREAKDOWN OF ERRORS.

Result	Count	%
Temporary Channel Failure	47341	31.58
Unknown Peer	23839	15.90
Channel Disabled	1203	0.80
Payment Timeout	336	0.22
Insufficient Fee	192	0.13
Expiry Too Soon	142	0.09
Other	267	0.18

timeouts are particularly rare. These errors indicate that the payment has taken longer than four minutes to return. When these errors occur they lock the funds in place until the payment returns, and in some situations channels have to be closed to recover the funds. This can be a costly (due to Bitcoin transaction fees) and lengthy process.

Figure 2 breaks the errors down by payment volume, grouping rare errors together. While the percentages of errors vary by volume, the relative proportions are very similar between volumes. We find that probed channels generally either do not return the *Unknown Peer* error at all, or they return it consistently. Of the more than 30k channels we probe, 6550 return the error on every probe. This suggests that over the probing period of a couple of weeks, the nodes at either ends of these channels were either infrequently or never connected. Similarly, we also find that there are 1780 nodes over which we cannot route a single payment.

These numbers seem so high that we verify them with an alternative client after our main measurements. We temporarily connect a second client to the network and retry payments to the endpoints of channels where we received the *Unknown Peer*. The second client is successful in routing payments to about 20% of these nodes. While this seems a slight improvement, it still validates the overall frequency of this error.

We note that there is a risk for nodes that remain disconnected over longer periods of time while keeping channels open. The respective endpoints of the channels may unilaterally try to close the channel and publish a signed transaction with an old channel balance. If this remains undetected for a longer period of time (for example, 24 hours), then the funds may be stolen without recourse. The concept of ‘watchtowers’ has been proposed to warn potentially affected nodes².

Key take-aways. Although many channels are reachable in principle, the Lightning Network is actually not capable of routing larger payments. Even modest payments of just US\$ 10 succeed only in less than half of all attempts; for larger payments around US\$ 50, the success rate drops to below 20%. No experiment run was ever able to reach more than a third of the destination nodes. At present, the Lightning Network is not capable of supporting the kinds of payments that would be needed to support activities such as shopping for everyday goods. This is due to insufficient funding of channels:

²<https://hedgetrade.com/what-are-lightning-networks-watchtowers/>

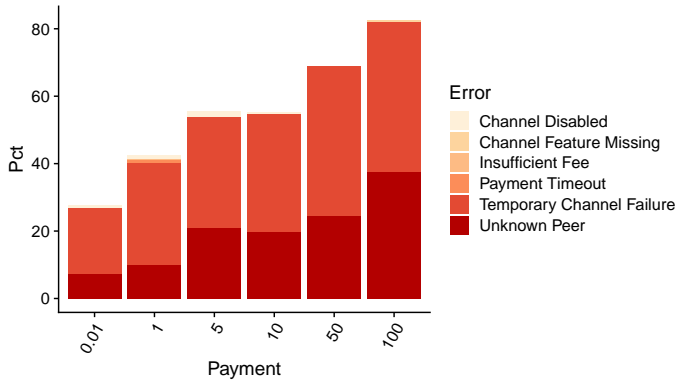


Figure 2. Errors during payments broken down by payment volume (US\$).

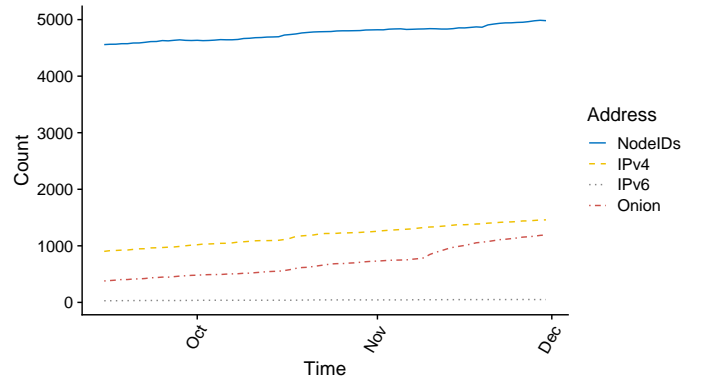


Figure 3. Development of the network layer: node IDs and network addresses.

even though many channels exist, they are often not able to forward a payment due to *congestion*: at the time we attempt a payment, it exceeds the channel’s currently available balance. A further, important reason is that the node corresponding to a channel’s endpoint is unavailable, often for long periods of time. This suggests that channel management could be improved.

B. Overall node availability on the network

More nodes in the network imply more available channels and a higher overall availability. We hence determine the network’s growth over time. Node churn is an important factor, however, as nodes should ideally stay well-connected in the network to sustain the overall reachability. We hence also measure how long-lived nodes are. Network location is an important factor related to this: nodes that run on publicly reachable servers can be expected to contribute more to overall reachability due to their uptime.

1) *Network growth*: Figure 3 shows the development of the Lightning Network according to the data from the *c-lightning* developers. We identify a slow but stable growth between 2019-09-15 and 2019-11-30: from 4558 Node IDs to 4981, *i.e.*, nearly 10% in 2.5 months. This corresponds to significantly fewer network addresses: just over 1000 IPv4 addresses are publicly known, and nearly as many onion addresses. This means many nodes do keep the privacy feature of not propagating their network address enabled.

Interestingly, IPv6 addresses are rare—we never find more than about 50. Using a second protocol can potentially improve overall availability. A number of nodes publish an IP address *and* an onion address. For example, 79 nodes choose to do this on 2019-09-15. This numbers grows to 182 by 2019-11-30. However, doing this breaks the anonymity of the respective NodeID as a receiver of payments. Either operators are not aware of this, or indifferent to it, or their primary goal is not their own anonymity but merely to help making forwarded payments as anonymous as possible.

We also determine the network addresses from the point of view of our Node B as of 2020-02-18 12:00 GMT, *i.e.*, 2.5 months later. At the indicated time, our node is aware of

4938 unique nodes (identified by their node ID). If we assume the Lightning Network maintained its growth after 2019-11-30, and assuming the growth rate remained about the same, this would imply our node is aware of about 90% of nodes in the network. For the 4938 nodes that Node B is aware of, we identify 2296 unique IPv4 addresses (a further 45 are in IANA-reserved prefixes, *i.e.*, invalid).

Our data from 2019 shows a relatively high number of onion addresses in the network until 2019-11-30. Our Node B identifies unique 1885 onion addresses on 2020-02-19, which indicates a definite growth since the end of our first observation period on 2019-11-30.

Our node set of 2020-02-19 11:30 GMT, which we obtain via the *listnodes* RPC call, contains 1882 onion addresses corresponding to 1843 nodes. 410 addresses use the older v2 addresses. These addresses use SHA1 and RSA-1024 cryptography, which offer less security against impersonation attacks and are slowly being phased out. Hidden services of v2 are also known to leak more information to Tor’s hidden directory services, an undesirable property. However, overall the choice of v2 addresses is not too concerning at this time, and the fact that the majority uses the newer v3 services is in fact encouraging.

2) *Liveness and churn*: We first use our data set from 2019 to check how long-lived nodes are. Comparing the node IDs from 2019-09-15 to the ones from 2019-10-15, we find that many remain in the network. Of 4558 nodes on 2019-09-15, 4038 are still there one month later. A further month on, this number drops to 3197, however.

Using our Node B, we estimate liveness and churn over the node’s observation period. Note that we do this for network addresses, not the public key-based identifiers. Of the 2251 public IP addresses where the Lightning software runs on port 9735, 73 are in IP ranges that are on our blacklist of networks that do not wish to be scanned. We choose the remaining 2178 addresses to scan TCP port 9735 and test their liveness. Only 875 nodes, corresponding to 859 IP addresses, respond on the port. This is a surprise as we use a version of *c-lightning* that is meant to prune stale nodes; hence the client should have a much more accurate picture of the network.

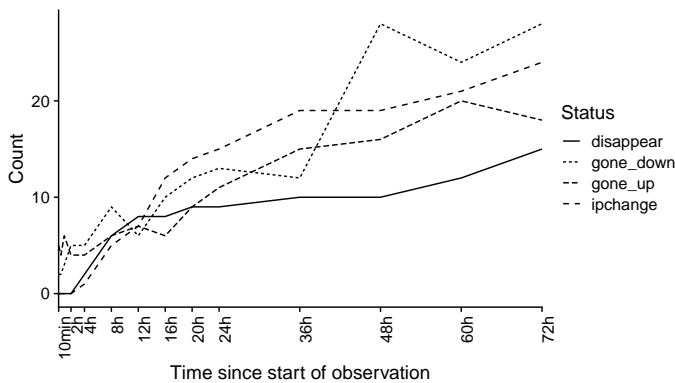


Figure 4. Network churn within three days.

We compute the IPv4 churn. We use the node set of Node B at the same time (2020-02-18 12:00 GMT) as the reference set of live and unreachable nodes. We then compare this to the node sets at the following times: 10, 30, and 60 minutes later; 2, 4, 8, 12, 16, 20, and 24 hours later; and 36, 48, 60, and 72 hours later.

We find that there is very little change in the network in terms of nodes remaining reachable or unreachable. Although two nodes become unreachable in the first ten minutes, 837 nodes are still reachable under the same IP address and port even after 72 hours (more than 95%). Figure 4 summarizes changes that occur over time. In the first 8 hours, there is very little activity: a handful of nodes (by node ID) disappear from the node set or become unreachable, but similar numbers also become reachable again. Larger changes become apparent only later. There is a jump in nodes that become unreachable after 12 hours, although a similar jump also occurs for nodes that become reachable. Overall, the network seems quite stable, and the churn is not a strong explanation for the observed stale addresses.

We choose the onion nodes for a manual liveness test as well. We enable use of the Tor daemon for our *c-lightning* client and attempt to connect to each onion address in turn. This is a lengthy process (13 hours). We successfully connect to 1297 of the addresses and fail in 546 cases. This indicates that onion addresses also suffer from the problem of staleness.

3) *Network locations*: We map the public IPv4 addresses to their corresponding ASes. We choose the 18th of 2019-09, 2019-10, 2019-11, and 2020-02 for this analysis. Table III presents the results. We first observe that the Lightning IP addresses are spread over a wide range of Autonomous Systems Numbers, and this number is increasing. In 2019-09, about 900 Lightning IPs are distributed over more than 250 ASNs (although we note that large corporations sometimes hold several ASNs). The top 5 AS owners between September and November 2019 are largely the same. We find hosting/cloud providers such as Google, DigitalOcean, Amazon, and OVH; however, we also find Internet access providers (Cogent, Comcast) with significant share. It would not be a surprise that Lightning nodes are run on cloud or hosting servers. This

has been well documented for the Bitcoin network itself [6].

The data from 2020-02 seem to show a reversal of the top-ranking entries. Cogent and Comcast together account for about 11% of the public IPv4 addresses. However, this changes when we filter out those IP addresses that *zmap* did not identify as live. Although Cogent remains in the first place, the remainder is made up of hosters. The tentative conclusion we offer here is that the network is moving towards central infrastructure, while at the same time spreading over more ASes and keeping a significant share of operators with classic ISP-based Internet access. This finding would be very consistent with the relatively low churn we estimate.

Key take-aways. The Lightning Network seems to grow at a moderate but steady pace. This is a good result for overall availability as every new node will also contribute at least one new channel. The high number of nodes that do not propagate their network addresses is remarkable: it means that nodes that wish to establish more channels are actually limited in their choice, which is contrary to the goal of decentralization. The network churn is quite low, which is a good result. We find that cloud providers feature prominently among the most important Autonomous Systems contributing to the network, which is indicative of centralization. The number of stale nodes is high, despite the protocol aiming to eliminate stale nodes from the network view. Even Tor nodes are frequently stale, hinting at operators not desiring to make a contribution to overall network stability and availability but rather focusing on their own privacy in more short-lived participation. Overall, the node availability on the network leaves considerable room for improvement as better availability would help sustain reachability.

VI. DISCUSSION

In the previous section, we identified a number of properties concerning the reliability of the Lightning Network network in terms of availability of payment routes and overall node availability in the network. We offer several thoughts based on our results in the context of the overarching goal of the network, which is to enable reliable payments while remaining decentralized. These two goals are conflicted. In our considerations, we lean towards favouring reliable payments over decentralization and privacy. Ultimately, this is a question of which *business model* the Lightning Network should operate under, which is a question for the community to decide.

a) *Ability to route payments*: The ability of the network to reach nodes via source routing (combining channels) is disappointing. Only small payments have a reasonable chance of success: 72% of payments of US\$ 0.01 and 58% of US\$ 1 were successful. However, these payments still reached only 35% of nodes at best. The success rate of payments beyond US\$ 50 was very low. A key reason for this is that channels simply do not have enough funding—transient errors due to insufficient balances are the most common. On the face of it, the Lightning Network will need to win users who are willing to invest more funds into channels. Naturally, this is a chicken-egg problem as lack of user base is a disincentive for investment. Investment

Table III
AUTONOMOUS SYSTEMS CONTAINING LIGHTNING NODES WITH PUBLIC IPV4 ADDRESSES, WITH TOP 5.

Time	IPs	Spread	1st (# nodes)	2nd (# nodes)	3rd (# nodes)	4th (# nodes)	5th (# nodes)
2019-09	901	258 ASNs	Google (116)	Comcast (50)	DigitalOcean (45)	Cogent (37)	OVH (21)
2019-10	1.1k	305 ASNs	Google (121)	DigitalOcean (57)	Comcast (56)	Cogent (49)	Amazon (28)
2019-11	1.3k	337 ASNs	Google (123)	DigitalOcean (70)	Cogent (63)	Comcast (62)	Amazon (35)
2020-02	2.3k	471 ASNs	Cogent (141)	Comcast (133)	DigitalOcean (116)	Amazon (78)	Google (78)
2020-02 (live)	858	249 ASNs	Cogent (114)	DigitalOcean (59)	Amazon (38)	OVH (32)	Contabo (29)

by companies and appropriate marketing campaigns may be one way to address this; however, such undertakings tend to de-emphasize decentralization.

b) Extending the protocols: A good part of our experiments failed due to the long-lived unavailability of a node representing a channel endpoint. As we actually measure relatively little churn in the network, at least in the public part of the network, the question is whether the Lightning protocol should be improved to eliminate stale information faster. Our results show that much stale information is kept by clients, despite a pruning mechanism in the popular *c-lightning* client. One can conceive a probing protocol that simulates payments (without requesting a particular amount) to test channel and node availability. Our recommendation is to add such a maintenance protocol to the network.

c) The right threat model for privacy: The argument against revealing public IP information is that it harms the privacy of operators, whose node IDs can be linked to their network address. This is likely to harm availability and actually pave the way towards more centralization as publicly known nodes are the only ones that new, joining nodes can connect to. The unavailability of more publicly known IP addresses also counteracts the goal of eliminating stale information as it makes it impossible to test a node’s (IP) availability directly. We believe that the feature of hiding the network address is based on a threat model that is inappropriate for Lightning Network. An IP address by itself does not reveal the operator’s identity, but a hoster or ISP will be able to map an IP address to a real person. Companies generally release customer data only to law enforcement agencies or other entities that can request such information, unless they are compromised and suffer a data breach. Hence, the only adversary that makes sense is one who falls into one of these two categories. Also note that, depending on the gravity of the underlying cause for a request to release customer information, it is conceivable that the requesting entities may be able to approach the hoster of a ‘hub node’, *i.e.*, the node with many channels and corresponding knowledge to which nodes and IP address they map—even if that hub is located in another jurisdiction. In such a case, the IP addresses of operators that have disabled the propagation of their network addresses is also given away. In summary, we believe that hiding the network address is of little benefit for the majority of the network while harming its development. Ideally, payments are routed in an onion-style anyway, which should already achieve a high level of privacy for many users and operators.

d) Business model and centralization: The above considerations imply that the corresponding design decisions should depend on the business model that Lightning operators wish to follow. Although the authors of [10] state that operating a node is currently not economically viable, this does not rule out that a dedicated, different business model may make Lightning both more performant and more profitable. Better funded channels, for instance, may attract more users and operators, hence improving the network’s performance and ability to route payments, which in turn may attract further users and investment. The community should engage in a discussion which direction the network should take.

VII. CONCLUSION

In this paper, we have contributed a study of Bitcoin’s Lightning network nearly four years after its inception. We focus on two aspects of availability that have seen little to no previous investigation, namely availability of payment routes and overall node availability in the network. These are necessary ingredients for the network to achieve reliable sending of payments. We find that we can theoretically construct paths to nearly all channels and nodes in the network. However, in practice routing payments fails much too often, in particular when trying to send larger payments in excess of US\$ 50. The reasons have to do with the network’s composition and slow reaction to stale information. This leads us to consider the question which changes to the Lightning Network’s structure, protocols, and business model could be made to improve its overall usefulness. While decentralization is a worthwhile goal, some improvements may well be easier to implement against the background of a business model involving central hubs. However, Bitcoin’s philosophy was always one of decentralization and enabling better privacy for digital payments. This remains a central tenet for many users and operators. We believe our findings should at least generate a discussion which direction the network should take.

We note that research on the Lightning Network should not end even if a new, more investment-based business model is adopted and leads to more centralization and less privacy. Assuming the network begins to carry sizable volumes, it will be an interesting research question whether attacks against hub availability benefit the attackers sufficiently in terms of stealing channel funds or destroying user trust, for example. As a cryptocurrency and community-based project, a growing Lightning Network should be continued to be monitored.

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