On the Routing Convergence Delay in the Lightning Network

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Abstract. Nodes in the Lightning Network synchronise routing information through a gossip protocol that makes use of a staggered broadcast mechanism. In this work, we show that the convergence delay in the network is larger than what would be expected from the protocol's specification and that payment attempt failures caused by the delay are more frequent, the larger the delay is. To this end, we measure the convergence delay incurred in the network and analyse what its primary causes are. Moreover, we further investigate and confirm our findings through a time-discrete simulation of the Lightning Network gossip protocol. We explore the use of alternative gossip protocols as well as parameter variations of the current protocol and evaluate them by the resulting bandwidth usage and convergence delay. Our research shows that there are multiple ways of lowering the convergence delay, ranging from simple parameter changes to overhauling the entire protocol.

Keywords: Bitcoin · Lightning Network · Gossip · Convergence Delay.

1 Introduction

Since its inception in 2008, the Bitcoin [8] network showed an inability to scale to a high volume of transactions [13]. The Bitcoin Lightning Network [11] is a second-layer payment channel network (PCN) that enables a high volume of low-cost off-chain Bitcoin transactions.

In the Lightning Network, nodes route payments by finding a path to the destination based on a local copy of the public channel graph that each node maintains. In order to keep their channel graph views in sync, nodes propagate update messages via a peer-to-peer gossip protocol that utilizes a so-called *staggered broadcast* mechanism. As a result of the gossip protocol, it can—in the worst case—take more than 10 minutes for a message to reach all nodes in the network.

To avoid issues caused by stale routing information, a convergence delay of this magnitude goes against the common goal of routing protocols to reach convergence quickly and reliably. The larger the convergence delay is, the more likely it is for payment attempts to fail since a source node might be computing a route based on stale information. Payment attempt failures stemming from the convergence delay currently account for roughly 1.24% of all failures according to [14]. These failures can not be eliminated completely given that message propagation cannot be instant. Moreover, improved routing algorithms such as multi-part payments (MPPs) do not improve the rate at which these failures occur. In fact, they may even increase their occurrences as the probability of such failures only increases with the number of channels involved in a payment.

In this work, we investigate the convergence delay of routing information and its effects on payments in the Lightning Network. Our main goal is to present the state of the convergence delay in the Lightning Network, the issues it causes, and to layout potential improvement ideas. Our contributions can be summarized as follows:

- We analyze the Lightning Network's gossip protocol in its current state by looking at and comparing c-lightning and LND, the two most popular node implementations. We measure the delay seen in the real network through a passive experiment and catalog the seen gossip messages (specifically all channel updates) to understand why and when gossip messages are broadcast by nodes. The catalog is also useful to understand which types of channel updates are potentially disruptive to payment routing. (Section 3)
- We implemented a simulator capable of simulating the Lightning Network's gossip protocol as well as payments in the Lightning Network. We can bootstrap our simulation from historical topology data and replay recorded gossip messages. We use the simulation to gain further inside into how the gossip protocol operates and where its inefficiencies lie. (Section 4)
- We evaluate the use of alternative message propagation mechanisms in the Lightning Network. Through simulation, we compare flooding, a structured broadcast utilizing the channel graph topology, inventory based gossip, as well as efficient set reconciliation using Minisketch [4]. (Section 4)

To our knowledge, there exists no prior related work on the convergence delay in the Lightning Network. However, there is a long history of convergence delay research in internet routing through the Border Gateway Protocol (BGP), which we use to draw inspiration for potential improvement ideas [1, 2, 7]. We discuss these and other related works in Section 6. In the following, we give a primer on information propagation and the convergence delay in the Lightning Network.

2 Information Propagation in the Lightning Network

The Bitcoin Lightning Network [11] is a second-layer payment channel network (PCN) that enables a high volume of low-cost off-chain Bitcoin transactions. A payment channel describes a type of smart contract that enables two parties to transact off-chain, with the only bottleneck being the network latency between

the two parties. A PCN enables payments between nodes that do not have direct channels with each other by routing payments over intermediary nodes to reach the destination. In order to ensure that payment forwarding requires no trust towards these intermediaries, such multi-hop payments are secured through so-called *Hash Time Locked Contracts* (HTLCs). Candidate routes are discovered by the originators through a source-routing algorithm operating on a local copy of the network graph, i.e., the routing information base (RIB). These local information are regularly kept in sync by gossiping update messages in the network.

The channel_announcement, node_announcement and channel_update messages are the three main messages of the Lightning Network's gossip protocol. Channel announcements are used by two nodes to prove that there is a channel between them. The proof comes in the form of four signatures tying the nodes to the keys used in the funding transaction. Node announcements are used to provide additional information about a node such as reachable network addresses. Channel updates provide routing information for a channel edge, such as routing fees and lock times. Each channel counterparty is able to broadcast a channel update for its outgoing channel edge. In order for a channel to be operational the network has to see three messages, one channel announcement and two channel updates (one for each edge of the channel).

2.1 Influences on the Convergence Delay

While the details of the information dissemination protocols are left to the implementations, the most common implementations, such as c-lightning³ and LND⁴, generally follow the same concepts. As we show later, the concepts presented in the following and their concrete parameterizations can have a significant impact on the convergence delay.

Staggered Broadcast. The gossip protocol of the Lightning Network uses a staggered broadcast that acts as a natural rate limiting mechanism to ensure that the network is resistant to certain types of denial-of-service (DoS) attacks. In a staggered broadcast, each node listens for gossip messages for a specified interval (stagger interval) before broadcasting all messages to a subset of peers. While listening, messages concerning the same channels are deduplicated by the timestamp field provided in the messages. If two channel updates for the same channel edge are seen, only the most recent update is kept in the broadcast queue. The value chosen for the stagger interval has a big impact on the convergence delay, since the higher it is the longer messages take to reach a majority of nodes. The specification⁵ recommends a 60 second stagger interval.

³ https://github.com/ElementsProject/lightning

⁴ https://github.com/lightningnetwork/lnd

⁵ https://github.com/lightning/bolts

	c-lightning	LND
Staggered Broadcast	60 second stagger interval.	90 second stagger interval, batches are broadcast in 5 second intervals.
Gossip Syncers	Five syncers, individual rotations every hour.	Three syncers, one being rotated every 20 minutes.
Rate Limiting	One channel update per day, burst up to 4.	One channel update per minute, burst of up to 10.

Table 1: Comparison of c-lightning and LND with regard to the most influential concepts on the convergence delay.

Gossip Syncers. The gossip_timestamp_filter message allows nodes to manage from which peers they want to receive new gossip. Not sending the filter message is equivalent to not requesting any gossip. By default, nodes only send filters to a subset of their peers, which are called active gossip syncers, while all other peers are passive gossip syncers. The number of active syncer connections each node maintains has an impact on the convergence delay since it determines how well nodes are connected. The more active syncer nodes choose the faster messages will propagate.

Rate Limiting. While the staggered broadcast already offers a form of rate limiting, nodes in addition apply a second rate limit on a per-edge basis. Only a certain number of updates from the same edge are allowed for each rate limiting interval. Such policies exist to prevent nodes from spamming the network with channel updates, but also to prevent I/O DoS attacks, since nodes write new channel updates to disk. A third rate limiting applies to redundant channel updates (only differing in the timestamp of the message), which are also considered as keep alive updates. A node will broadcast keep alive updates to indicate that its channels are still active and should not be pruned from other nodes' views of the network. To rate limit keep alive updates, nodes usually only allow them in a defined frequency, but the details differ from implementation to implementation.

Comparing Node Implementations While the Lightning implementations generally follow the concepts just discussed, the specific parameters used by these implementations can differ quite a bit. In the following, we therefore discuss the relevant details of the two most popular implementations of the Lightning Network protocol, c-lightning and LND.

As also shown in Table 1, the behavior of ${\tt c-lightning}$ generally sticks to the specification's guidance, while LND differs from it significantly with a stagger interval of 90 seconds. When the timer expires, all seen messages are split up into batches and broadcast to all relevant peers in 5 second intervals. The function for calculating the batch size from the total number of messages n to broadcast

is the following:

$$sb(n) = min\left(10, \frac{n \cdot 5s + 90s - 1}{90s}\right)$$

The number of broadcast batches increases with the number of messages, but is capped at 18 in order to prevent the overlapping of stagger intervals. With 5 seconds between batches and a maximum of 18 batches, the last message may potentially be broadcast $17 \cdot 5 = 85$ seconds after the stagger timer expires. A plot of sb(n) can be seen in Figure 1a. Only if there are more than 162 messages seen per 90-second stagger interval, all 18 batches will be filled. If the general rate of messages in the network is lower than that, less batches will be used lowering the convergence delay.⁶

The rate limiting policies of these two node implementations do not play together without friction. If a channel is updated once per minute, a c-lightning node would disregard all updates after the fourth for up to one hour, while a LND node would happily accept all updates. The c-lightning node will not relay disregarded updates, which can cause the convergence delay for these updates to increase. However, this is not an observable issue, since the majority of nodes are running LND.

3 Gossip Traffic Analysis

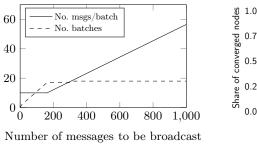
In the following, we describe our methodology for measuring and analysing gossip traffic in the Lightning Network.

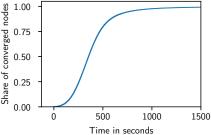
3.1 Measuring the Convergence Delay

In order to measure the convergence delay in the Lightning Network, we used the python $pyln-proto^7$ package to connect to and communicate with nodes on the network. The node addresses were extracted from a topology snapshot collected from an LND node right before the start of the experiment (Oct. 30, 2021). We connected to as many nodes as possible and chose all of them as our active gossip syncers. We recorded all received messages including at which times $\{t_1, \ldots, t_n\}$ and from which node we got the message. The recorded timestamps can then be used to estimate the convergence delay in the network by looking at the difference between the first and last timestamp. This estimation method assumes that the first timestamps in these lists correspond to the time of initial broadcast and that all nodes have seen the message after the last timestamp.

⁶ The stagger interval was increased in January 2019 from 30 to 90 seconds with the reasoning to lower bandwidth usage by slowing the propagation of messages [10]. In April 2019, the sub-batch broadcast was introduced with the reasoning to eliminate bursty resource usage after the stagger timer expires [6]. We could not find records of detailed discussion on how the exact parameter values for these changes were chosen.

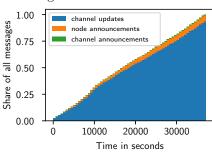
⁷ https://github.com/ElementsProject/lightning/tree/master/contrib/pyln-proto

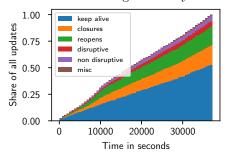




- - (a) LND batch sizes.
- (b) Measured convergence delay.

Fig. 1: LND's broadcast batching and measured convergence delay.





- (a) Observed shares of update messages.
- (b) Channel updates cataloged by type.

Fig. 2: Categorization of observed gossip messages.

In total, we received 69,942 unique gossip messages from 1,046 nodes over a time span of close to 10 hours. To estimate the convergence delay, we used all messages that were received at least from 500 different nodes.

Figure 1b shows the share of nodes that have seen a message in relation to the time since initial broadcast: the average time it takes for a node to see a message is 359.9 seconds, with 95% of nodes seeing messages after 753 seconds and 100% of nodes seeing messages after 2,500 seconds.

3.2Dissecting Recorded Gossip

We then categorized the collected data and examined which share of gossip messages are node announcements, channel announcements or channel updates. We also analyzed the contents of all channel updates to understand when nodes send updates and how they typically update channel policies.

As seen in Figure 2a, the rate at which new messages arrive is more or less constant. Of all messages we recorded, 5.13% were node announcements, 0.34% were channel announcements and 94.53% were channel updates. This distribution matches our expectations, as channel announcements are directly rate limited by the blockchain, node announcements only need to be broadcast

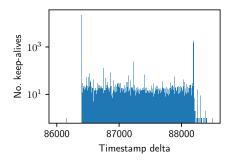
infrequently to modify network addresses or add new feature announcements, and channel updates change channel policies, which happens regularly over the course of a channel's lifespan.

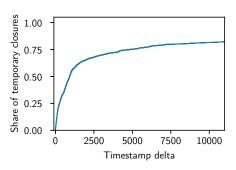
We categorized channel updates into six different categories:

- Keep-alive updates only differ in the timestamp field. These updates are meant to tell the network that a channel is still active. They made up 45.32% of all recorded messages.
- Channel closure updates close a channel temporarily or permanently. Temporary channel closures can happen if a peer goes offline due to network issues, in which case the other peer will broadcast such an update to inform the network not to route over the offline peer. These updates made up 19.29% of all recorded messages.
- Channel re-open updates open a channel that was previously closed. These updates made up 18.66% of all recorded messages.
- Disruptive updates change the channel policy in a way that could cause payment failures, if the payment source does not know of the update. Channel closures are excluded because we categorize them separately. Disruptive updates made up 8.57% of all recorded messages.
- Non-disruptive updates change the channel policy in a way that could cause a payment source to over-pay on fees or use a higher lock time than needed. These updates made up 7.22% of all recorded messages.
- Misc. updates are all other updates that we saw. For example, updates that change the htlc_minimum_msat field fall into this category. These updates made up 0.99% of all recorded messages.

The observed amount of keep-alive updates is slightly concerning, as they make up roughly 50% of all seen updates. This amount of keep-alive updates cannot be explained by nodes broadcasting them at a reasonable rate. In theory, a keep-alive only has to be sent for channels that did not have an update within 14 days. Therefore, transmitting a keep-alive update every 13 days should be sufficient to prevent other nodes from pruning the channel. Figure 3a shows the difference in the timestamp field between the keep-alive and the previous update: we observe that for almost all of the keep-alive updates the differences lie between 86, 400 and 88, 200 seconds, which corresponds to exactly 1 day and 1 day plus 30 minutes. We found that LND nodes are responsible for these updates, because they check every 30 minutes if any of their channels had an update within the last day, and will broadcast a keep-alive update otherwise. However, we were not able to explain the large peaks seen in Figure 3a at the interval boundaries. Moreover, we did not observe any keep-alive updates with a smaller difference, because LND nodes do not relay such updates and therefore they do not propagate through the network.

Looking at the timestamp differences for all updates in our channel re-open category (cf. Figure 3b), we see that most channels edges that get re-opened were disabled for short periods of time. For example, 60% of edges were closed for less than 22 minutes. This is likely caused by network issues that lead nodes to temporarily disable edges.





- (a) Time since last keep-alive.
- (b) Cumulative channel closure durations.

Fig. 3: Timestamp differences of keep-alive and channel closure updates.

4 Simulation Study

In the following, we discuss the conducted model-based simulation study on the routing convergence delay in the Lightning Network.

4.1 Simulation Model

The behavior of real-world peer-to-peer networks is influenced by many different variables. Nodes participating in such networks can be diverse in geographical location, bandwidth restrictions, software implementation, software version or configuration, and simulating all different permutations is simply not feasible. In the context of investigating the gossip protocol of the Lightning Network, we restrict the scope of our simulation by making the following assumptions: if two nodes are connected through a channel, they have a constant TCP connection. The snapshot we use to bootstrap our simulation contains all nodes and all channels that exist in the network. We ignore any non-listening nodes that were not announced to the network, as well as private channels. Our simulation propagates node and channel announcements, but does not actually add them to the simulated topology. Only channel updates are applied to the simulated topology. The gossip algorithm is the main influence on the convergence delay, and we do not simulate other potential influences such as an overhead caused by cryptographic functions. Payments are atomic and instant. All nodes in each simulation follow the same gossip protocol. All nodes have the same bandwidth of 1 MB/s in up- and download.

We chose to implement our discrete-event simulator⁸ in the Go programming language and bootstrap the simulation from historical topology snapshots that were extracted from an LND node with a fully synced network graph. These snapshots contain a list of nodes and channels which we use to build our simulation network. The snapshot we use for all simulations contains 17, 332 nodes, 77, 921 channels and was taken on Oct. 30, 2021. In order to simulate a realistic amount

⁸ https://github.com/dergoegge/lnconv-paper-sim

of traffic, we replay gossip messages that we recorded in the real network. This works well as most gossip messages can be traced back to an origin node in the network as long the snapshot we use to bootstrap the simulation is not much older than the start of the recorded period. For messages for which we could not find an origin in our snapshot we choose a random origin. Bandwidth is modeled by each node having an incoming byte counter that gets incremented with every message that is being downloaded and decremented with every message that is fully received. The arrival time of a new message is calculated based on a fixed bandwidth, the number of incoming bytes and a fixed latency overhead of $100\,ms$.

4.2 Simulation Results

In this section, we present the data collected on an LND simulation scenario in which we replayed the first hour of the gossip we recorded in Section 3, consisting of 7,217 network messages. We simulate 100,000 payment attempts which were uniformly distributed over the hour. Payment sources and destinations are chosen randomly and the payment amount is set to $1\,sat$ in order to reduce interference by failures originating from anything else than outdated routing information.

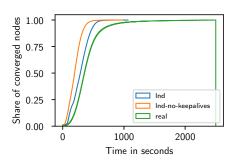
Bandwidth. The simulated network transferred a total of $40.77\,GB$ to deliver the 7,217 messages to all nodes. The theoretical lower bound for bandwidth usage B_{min} is the product of the number of all nodes, the total number of messages and the average message size, i.e.,

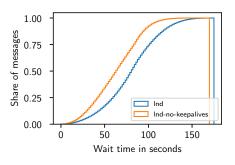
$$B_{min} = num_nodes \cdot num_messages \cdot avg_message_size$$

Assuming all messages are channel updates with a size of $128 \, bytes$, $B_{min} = 16.01 \, GB$. We therefore found that the network uses $2.55 \, times$ the theoretically needed bandwidth B_{min} .

Redundancy. 6.29% of messages will be seen only once, 33.28% will be seen twice, 59.93% will be seen three, and 0.5% will be seen four times. All nodes have 3 active gossip syncers which explains why most messages are seen three times or less. A message is only seen 4 times if it is received as part of the initial broadcast, which goes out to all connected peers. On average each message is seen 2.55 times. Note that this is the same factor as the one from our bandwidth calculations: every message that is received more than once is exactly the overhead to a perfect broadcast in which every message is received only once by each node.

Convergence Delay. We measure the convergence delay by recording how long it takes a message to be seen for the first time by every node. This is very similar to the measurements conducted in Section 3, but within a simulation we get much more accurate data since we have an omniscient view. Figure 4a compares the convergence delay we recorded in the real network to the one we observed





- (a) Measured vs. simulated conv. delay.
- (b) Queue waiting times.

Fig. 4: Convergence delay and broadcast queue waiting times in a simulated network consisting only of LND nodes.

in the simulation. In our simulation, the average time it took for a node to see a message is 291.21 seconds, with 95% of nodes seeing messages after 510 seconds and 100% of nodes seeing messages after 1,075 seconds. The convergence delay seen in the simulation slightly differs from the delay measured in the real network with messages in the simulation propagating faster after initially being broadcast and messages taking longer to reach all nodes in the real network. From 20% to 80% of nodes having seen the messages it takes 240 seconds in the simulation while in took 265 seconds in the real network.

As mentioned previously, roughly 50% of the messages that we recorded are keep-alive updates. We ran a simulation without the keep-alive updates (lnd-no-keepalives) and found that the convergence delay was significantly reduced, with 95% of nodes converging after 374.19 instead of 510 seconds.

Waiting Times. Looking at the broadcast queue waiting times of messages we observed that waiting times and hence the convergence delay become larger the more messages are propagating through the network. This is explained by the sub-batch trickling approach that LND has chosen which makes waiting times dynamic to a certain degree. The growth of waiting times is bounded by the maximum number of sub-batches that LND will send. A plot of the waiting times can be seen in Figure 4b. The minimum waiting time is 0 seconds and the maximum is 175 seconds. A message will wait 175 seconds, if it arrives at the beginning of the 90 second stagger interval and gets broadcast in the last sub-batch, 85 seconds after the stagger timer ticks.

Failed Payment Attempts. Out of the 100,000 tried payment attempts, 42% were successful and 58% failed. 0.114% of attempts failed because the payment source did not have a recent update for one of the channel edges in the payment route.

As we have seen, the staggered broadcast is quite inefficient in its bandwidth usage with messages being seen 2.55 times on average by the same node and

Algorithm	Conv. Delay	Bandwidth Usage	Payment attempts
lnd	509.75s	$40.47\mathrm{GB}$	602
lnd-t1s	312.65s	$39.36\mathrm{GB}$	349
lnd-sb100	266.54s	$38.9\mathrm{GB}$	316
<pre>lnd-inv</pre>	509.46s	$19.26\mathrm{GB}$	592
<pre>lnd-inv-t1s</pre>	313.45s	$19.41\mathrm{GB}$	394
lnd-inv-sb100	267.93s	$20.23\mathrm{GB}$	274
c-lightning	101.29s	$59.52\mathrm{GB}$	171
c-lightning-inv	103.2s	$26.36\mathrm{GB}$	161
spanning (BFS)	1.11s	$15.7\mathrm{GB}$	5
flooding-4	2.72s	$50.7\mathrm{GB}$	3
flooding-8	1.72s	$94.7\mathrm{GB}$	1
flooding-16	1.16s	$180.92\mathrm{GB}$	2
flooding-32	0.82s	$353.21~\mathrm{GB}$	4
minisketch-4	19.25s	$19.15\mathrm{GB}$	33
minisketch-8	20.24s	$19.84\mathrm{GB}$	43
minisketch-16	20.7s	$21.45\mathrm{GB}$	43
minisketch-32	20.54s	$21.46\mathrm{GB}$	30

Table 2: Convergence Delays (95%), bandwidth usage, and unconverged payment attempts.

95% of nodes converging after 510 seconds. The share of unconverged payment attempts (0.114%) does not seem that problematic but it could be argued that in absolute numbers the total number of unconverged payment attempts can still be large. The research by Waugh and Holz suggests that this rate is actually higher at around 1.2% [14]. Exploring alternative gossip algorithms seems worthwhile based on these results.

4.3 Evaluating Alternative Gossip Strategies

In this section, we layout ideas for potential alternative gossip algorithms that the Lightning Network could employ. We use our simulator to compare the different algorithms and evaluate the feasibility of these alternatives being used in the real network based on bandwidth usage, convergence delays, and their impact on payment attempts. We compare the following alternative strategies: flooding, a structured broadcast using a global spanning tree, inventory based gossip, parameter variations of the current protocol, as well as set reconciliation using Minisketch [4].

We compare all alternative strategies to each other and the simulation data from Section 4.2. We specifically compare bandwidth usage, convergence times and the number of unconverged payment attempts and simulate each algorithm using the same snapshot and replaying the same messages as before (17,332 nodes,77,921 channels,7,217 messages over 1 hour,100,000 payment attempts). The convergence delays and bandwidth usage for all the different algorithms are listed in Table 2.

As expected, flooding has the highest bandwidth usage with low convergence delays and the spanning tree algorithm (global tree constructed using breadth-first search) has the lowest bandwidth usage and the lowest convergence delay. With flooding, we see the bandwidth consumption scaling proportionally with increased connectivity (number of active syncer connections). The convergence delay is naturally smaller with increased connectivity.

LND's choice of staggered broadcast parameters results in a roughly five times increase in the convergence delay compared to c-lightning. While LND's approach leads to a larger convergence delay it also reduces bandwidth usage by about 33%. We simulated two variations of LND's algorithm, one with a minimum sub-batch size of 100 instead of 10 messages (lnd-sb100), and one with a sub-batch delay of one instead of five seconds (lnd-t1s). Both of these parameter changes lead to faster messages broadcast after the stagger timer expires leading to an decrease in convergence delay of 39% for lnd-t1s and 48% for lnd-sb100.

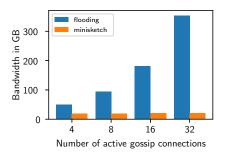
Inventory-based protocols announce a shortened version of the full message to give the receiver the chance to only request the full message once. For gossip messages in the lightning network, the size of an inventory message can be 64 bits [12]. We see that inventory based protocols reduce bandwidth usage significantly when compared to their regular variants. With lnd-inv requiring 52.4% less bandwidth than lnd and c-lightning-inv requiring 55.7% less bandwidth than c-lightning. The convergence delays however are unaffected by the decrease in bandwidth usage. Usually it would be expected that latency increases with an inventory-based gossip protocol but the extra round trip has no impact here, given that the stagger interval is multiples larger than the round trip time.

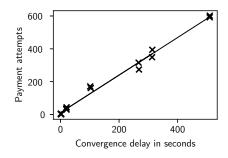
In Figure 5a, we compare the bandwidth usage of flooding and set reconciliation, in relation to the connections made by each node. Our set reconciliation algorithm is based on the Erlay protocol that was proposed for the transaction relay in the Bitcoin network [9]. In our protocol, we implemented no fan-out flooding and hence all messages are exchanged via set reconciliation. We observe that bandwidth usage does not increase proportionally with the number of connections made for the set reconciliation protocol. Instead, the bandwidth usage scales with the rate of messages in the network, just like the Erlay protocol.

We observe that the number of unconverged payment attempts is highly correlated with the convergence delay. We do not distinguish between failed payment attempts and attempts that arise due to opportunity costs, as the combined number of these attempts is sufficient in evaluating different protocols. As seen in Figure 5b, based on our limited data set of the different algorithms, the relationship between the convergence delay and the number of unconverged payment attempts is linear. The lower the convergence delay, the fewer unconverged payment attempts can be observed.

5 Discussion

The staggered broadcast protocols rate-limit the propagation of channel updates by de-duplicating updates for the same channel with in the stagger interval. This





- (a) Bandwidth usage vs. increased connectivity.
- (b) Unconverged payment attempts vs. convergence delay.

Fig. 5: Simulated parameter interdependencies.

means that a node will only forward one channel update for the same channel edge in every stagger interval. No potentially important updates are discarded, since the newest update that was seen will always be forwarded. This form of rate limiting prevents the network from witnessing rapid changes in channel policies, while still propagating the newest updates. The propagation of the newest updates is significantly delayed as we have shown through the simulations and measured in Section 3. We argue that this form of rate limiting implicitly discourages frequent channel updates at the cost of delivering the newest updates with large delays. Explicitly discouraging frequent updates through strict perchannel rate limiting as discussed in Section 3 could be well suited for some of our alternative protocols that aim to deliver messages faster. A strict rate limit would discard newer updates that violate the rate limit, so honest nodes should never broadcast messages for the same channel in violation of the limit.

LND's choice of parameters for its staggered broadcast is a bit of a mystery, since there is no public record on how the exact values were chosen. However, broadcasting messages in sub-batches instead of one large batch after the stagger timer expires is a good choice to reduce bursty resource usage. We would however recommend that the LND developers revisit their choice of parameters for the staggered broadcast, because reducing bandwidth usage by 33% while increasing the convergence delay by a factor of five does not seem like a reasonable trade-off (compared to parameters mentioned in the specification). As we have shown through the simulations, adjusting the parameters can have a big impact on the convergence delay. Adjusting these parameters would be the least complex software change to address the large convergence delay, while maintaining the rate limiting properties of the staggered broadcast.

Introducing an inventory-based gossip protocol reduces the bandwidth usage without changing the convergence delay at all. In combination with adjusting the parameters of the staggered broadcast the convergence delay could also be lowered. An inventory-based gossip protocol could remain a staggered broadcast and thereby maintain its rate limiting effect without introducing strict rate limiting

iting. The added software complexity of an inventory-based gossip is fairly low and there already exists a proposal on the specification [5].

Increasing the number of connections that nodes make to gossip (connectivity) can lead to better reliability in adversarial environments. With low connectivity an attacker has to control less connections to be able to censor information from reaching a victim. For some protocols an increase in connectivity can also lead to a reduction in convergence times because the spread factor is higher.

Even though the spanning tree protocol seems great based on the results, it is not a great fit for the real network. As mentioned earlier, the protocol makes the assumption that all nodes agree on the exact same static spanning tree, which would not trivially work in the real network. A single tree is also not going work for security and reliability reasons. If one node in the tree goes offline, none of the nodes in its sub-tree would receive new messages. Introducing multiple trees to gain redundancy would increase the bandwidth usage which makes using a spanning tree less desirable in the first place. A spanning tree protocol with multiple trees would probably turnout to be similar in efficiency to a flooding protocol.

A flooding protocol comes with a small convergence delay of one to two seconds but increases bandwidth usage above that of the current algorithm (lnd). Bandwidth usage increases linearly with increased connectivity. If an increase in connectivity is wanted then flooding would not be suitable. In fact all protocols besides set reconciliation lead to a proportional increase in bandwidth with increased connectivity.

Compared to the other protocols, set reconciliation has a small convergence delay and low bandwidth usage. Increasing connectivity is also possible without increasing bandwidth usage, as the bandwidth usage scales with the rate of messages seen in the network. Introducing set reconciliation comes with much greater software complexity than any of the other protocols. Multiple new message types would need to be introduced and the Minisketch library adds a dependency.

Decreasing the number of unconverged payment attempts can also be done without changing the gossip protocol. Nodes could temporarily allow payments that use old channel policies, after broadcasting a new policy. This would work well for fee or lock time adjustments. In the end this depends on the channel owners preferences on whether or not they want updates to immediately take effect.

6 Related Work

The explosive growth of the internet in its topological complexity as well as user count has led to a lot of research on the convergence delay for routing protocols, such as the Border Gateway Protocol (BGP). Large convergence delays in BGP can cause routing failures similar to how large convergence delays in the Lightning Network can cause payment failures. Labovitz et al. showed through a 2-year study that the convergence delay of BGP was much higher than previously expected. By injecting routing events to simulate failures and collecting

data on these events, the authors were able to figure out the convergence delay for different types of events. Convergence delays were primarily caused by different router vendor's implementations of the BGP specification with regard to the choice of timer values [7]. da Silva and Souza Mota suggested ways on how to lower the BGP convergence delay which included adjusting timer values of implementations and centralizing control of networks [2]. Ben Houidi et al. investigated slow BGP table transfers which increase the convergence delay. They found that gaps, in which both sender and receiver are idle, during table transfers are a common occurrence caused by timer driven implementations, with different vendors choosing different timer values [1]. Similar to this BGP research, we found that a big part of the convergence delay in the Lightning Network is driven by the parameter choices for the staggered broadcast of different implementations.

Decker and Wattenhofer measured block propagation times in the Bitcoin network and verified that the propagation time is the primary cause for forks in the blockchain. They measured the propagation times by connecting to a large number of nodes and listening for block announcements. With this setup they recorded when blocks where seen and from which nodes. From this data they are able to estimate how long it takes blocks to traverse the network after the initial broadcast [3]. Our work is methodically similar, since we also measure the convergence delay in the Lightning Network by connecting to many nodes in the network and record arrival times of messages.

Naumenko et al. proposed Erlay, a protocol for transaction relay in the Bitcoin network that makes use of efficient set reconciliation in combination with flooding. It aims to lower the bandwidth requirements needed for transaction relay with the trade-off of higher latency. The authors evaluated the bandwidth and latency trade-off of Erlay and compared it to the current flood-only protocol [9]. We used the Erlay protocol as inspiration for simulating a similar protocol in the Lightning Network and specifically used their prior research when choosing the parameters for our protocol.

Waugh and Holz studied availability and reliability properties of the Lightning Network. They tested the network's ability to route payments of different amounts and created a taxonomy of permanent and temporary failures that occurred. They looked at the availability of nodes in the network and measured how much churn (nodes joining and leaving the network) exists [14]. This work listed payment attempt failure types that were caused by outdated routing information, by probing the network with real payments. We only simulated payments to investigate these failure types.

7 Conclusion

In this work, we analyzed the convergence delay in the Lightning Network, described the effect it can have on payments, and evaluated alternative gossip protocols that could reduce the delay. We found the network to have a significant convergence delay, with 95% of nodes only having converged after roughly

10 minutes. A majority of the gossip traffic consists of redundant channel updates (keep-alive messages), which further increase the delay given the parameter choices of the LND implementation. Our simulations show that payment attempt failures due to unconverged routing information are rare (occuring in $\ll 1\%$ of payment attempts). However, the convergence delay may still be lowered while also reducing the bandwidth usage, either by switching to alternative gossip algorithms or adjusting the parameters of the current protocol. By switching to a set reconciliation based protocol, the connectivity of the network could be increased with nodes receiving gossip updates from more peers without suffering from significant increases in bandwidth.

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