Topological Analysis of Bitcoin's Lightning Network

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Abstract

Bitcoin's Lightning Network (LN) is a scalability solution for Bitcoin, which allows transactions to be issued with negligible fees and settle transactions instantly at scale. In order to use LN, funds need to be locked in payment channels on the Bitcoin blockchain (Layer-1), that one may use them in LN (Layer-2). LN is comprised of many payment channels forming a payment channel network. LN promises that a few payment channels already enable anyone to efficiently, securely and privately route payments across the whole network. In this paper we quantify the structural properties of LN and argue that LN's current topological properties largely harms its value proposition and potential.

Keywords: Bitcoin, Lightning Network, Network Topology, Payment Channel Network

1 Introduction

Recently the Bitcoin [3] network celebrated its 10th anniversary. During these years Bitcoin gained a huge popularity due to its publicly verifiable, decentralized, permissionless and censorship-resistant nature. This tremendous popularity and increasing interest in Bitcoin pushed its network's throughput to its limits. Without further advancements, the Bitcoin network can only settle 7 transactions per second (tps), while mainstream centralized payment providers such as Visa and Mastercard can process approximately 40,000 tps in peak hours. Moreover one might need to pay large transaction fees on the Bitcoin network, while also need to wait 6 new blocks to be published in order to be certain enought that the transaction is included in the blockchain.

To alleviate these scalability issues the Lightning Network (LN) is designed in 2016 [5], and launched in 2018, January. The main insight of LN is that transactions can be issued also off-blockchain in a trust-minimized manner achieving instant transaction confirmation times with negligible fees, whilst retaining the security of the underlying blockchain.

Bidirectional payment channels can be formed on-chain using a construction called Hashed Timelock Contracts (HTLC). Later several payments can take place in a payment channel. The main advantage of payment channels is that one can send and receive thousands of payments with essentially only 2 on-chain transations: the opening and closing channel transactions.

Using these payment channels as building blocks one might establish a

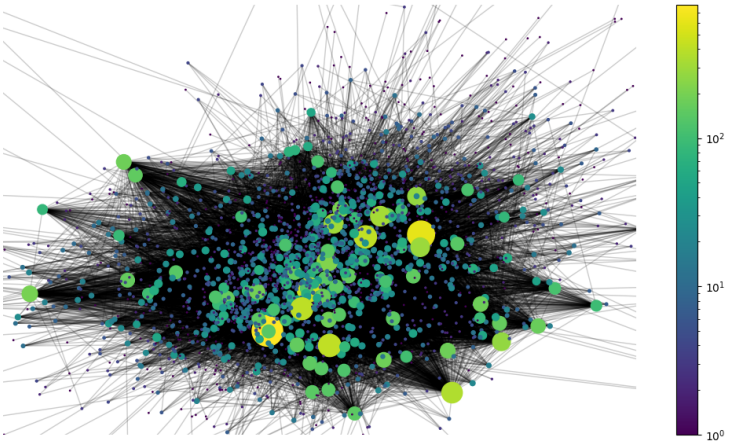


Figure 1: LN's topology. Nodes with higher degree are highlighted with lighter colors and larger circles.

payment channel network, where it is
not necessary to have direct payment channels between nodes to transact with each other, but they could simply route their payments through other nodes' payment channels. Such a network can be built, because LN achieves payments to be made without any counterparty risk, however efficient and privacy-preserving payment routing remains a challenging algorithmic task [6].

Our contributions. We empirically measure and describe LN's topology and show that it is utterly centralized and fragile against both random failures and targeted attacks. These findings suggest that LN, unlike Bitcoin, is undoubtedly far from being reliable, censorship-resistant, decentralized and private.

2 Lightning Network's Topology

LN can be described as a weighted graph $G = (V, E)$, where V is the set of LN nodes and E is the set of bidirectional payment channels between these nodes. We took a snapshot[1] of LN's topology on the 10th birthday of Bitcoin, 2019 January 3rd. In the following we are going to analyze this dataset.

LN gradually increased adoption and attraction throughout 2018, which resulted in 3 independent client implementations (c-lightning, eclair and lnd) and 2344 nodes joining LN as of 2019, January 3rd. The density of a graph is defined as $D = \frac{2|E|}{|V||V-1|}$ which is the ratio of present and potential edges. As it is shown in Figure 2. LN is quite a parse graph. This is further justified by the fact that LN has 530 bridges, edges which deletion increases the number of connected components. Although LN is consisted of 2 components, the second component has only 3 nodes. The low transitivity, fraction of present and possible triangles in the graph, highlights the sparseness of LN as well.

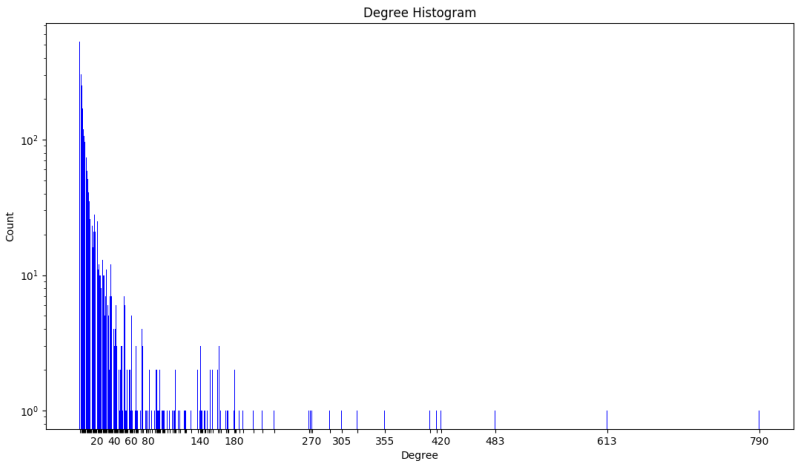
Number of nodes	2344
Number of payment channels	16617
Average degree	7.0891
Connected components	2
Density	0.00605
Total BTC held in LN	543.61855₿
s-metric	0.6878
Maximal independent set	1564
Bridges	530
Diameter	6
Radius	3
Mean shortest path	2.80623
Transitivity	0.1046
Average clustering coefficient	0.304
Degree assortativity	−0.2690

Figure 2: LN at a glance: basic properties of the LN graph.

However LN also exhibits somewhat scale-free properties as the s-metric suggests. S-metric was first introduced by Lun Li et al. in [2] and defined as $s(G) = \sum_{(u,v)\in E} deg(u)deg(v)$. The closer to 1 s-metric of G is, the more scale-free the network. Diameter and radius of LN suggests that LN is a small world. Somewhat scale-freeness is also exhibited in the degree distribution of LN. Majority of nodes have very few payment channels, although there are a few hubs who have significantly more connections as it can be seen in Figure 3.

Negative degree assortativity of the graph indicates that on average low degree nodes tend to connect to high degree nodes rather than low degree nodes [4]. Such a dissortative property hints a hub and spoke network structure, which is also reflected in the degree distribution, see Figure 3.

Figure 3: LN's degree distribution



Average shortest path length is 2.80623, which signals that payments can easily be routed with a few hops throughout the whole network. Although this is far from being a straightforward task, since one also needs to take into consideration the capacity of individual payment channels along a candidate path.

When a new node joins LN, it needs to select which other nodes it

[1] https://graph.lndexplorer.com

is trying to connect to. In every LN implementation one of the key goal of a node is to optimize its centrality by connecting to central nodes. This phenomena sets up a preferential attachment pattern. Betweenness centrality of a node v is given by the expression $g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$, where σ_{st} is the total number of shortest paths between node s and t, whilst $\sigma_{st}(v)$ is the number of those paths, that pass through v. Closeness centrality of a node v is defined as $CC(u) = \frac{N}{\sum_{u \neq v} d(u,v)}$, where N is the number nodes in the graph and $d(u, v)$ is the distance between node u and v. Closeness centrality measures how close a node is to all other nodes.

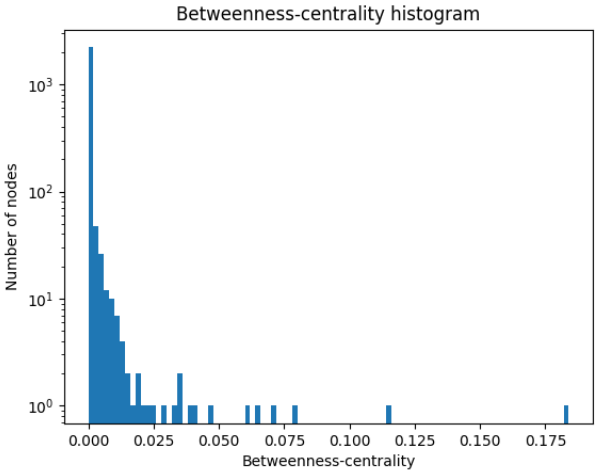


Figure 4: LN's betweenness centrality

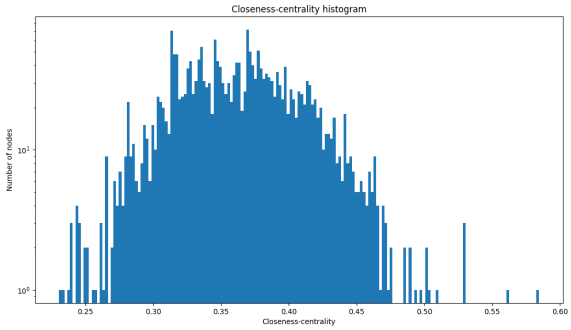


Figure 5: LN's closeness centrality

Small-world architectures, like LN, exhibit high clustering with short path lenghts. The appropriate graph theoretic tool to asses clustering is the clustering coefficient [7]. Local clustering coefficient measures how well a node's neighbors are connected to each other, namely how close they are to being a clique. If a node u has $deg(u)$ neighbors, then between these $deg(u)$ neighbors could be at maximum $\frac{1}{2}deg(u)(deg(u) - 1)$ edges. If $N(u)$ denotes the set of u's neighbors, then the local clustering coefficient is defined as $C(u) = \frac{2|(v,w):v,w \in N(u) \wedge (v,w) \in E|}{deg(u)(deg(u)-1)}$.

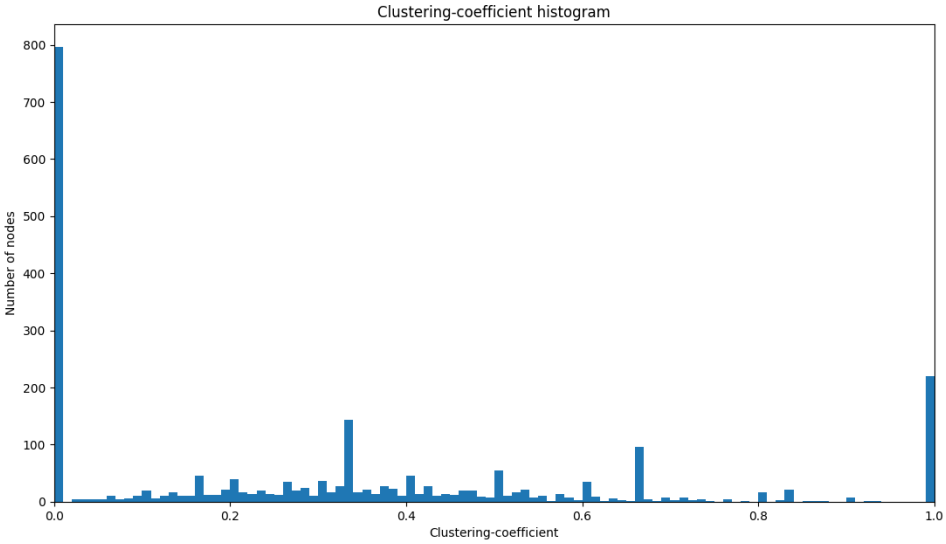


Figure 6: Local clustering coefficient of LN

LN's local clustering coefficient distribution suggestively captures that LN is essentially comprised of a small central clique and a loosely connected periphery.

3 Robustness of LN

It is a major question in network science how robust a given network is. LN, just like Bitcoin, is a permissionless network, where nodes can join and leave arbitrarily at any point in time. Nodes can also create new payment channels or close them any time. Furthermore as new payments are made, capacities of payment channels are changing steadily. Despite the dynamic nature of LN, its topology's characteristics remain constant after all. In this section we investigate how resilient is LN, whether it can effectively withhold random node failures or deliberate attacks.

3.1 Random Failures

Random failures are a realistic attack vector for LN. If nodes happen to be off-line due to bad connections or other reasons, they can not participate in routing payments anymore. Such a failure can be modeled as if a node and its edges are removed from the graph. We continually remove nodes from the graph, until the networks is broken into several isolated components. The fraction of nodes need to be removed from a network to break it into multiple connected components is called critical threshold and denoted as f_c. As Figure 7. displays LN is not capable of withstanding even random failures. This incapability is even more striking when compared to other real networks.

Network	f_c
Internet	0.92
WWW	0.88
US Power Grid	0.61
Mobil Phone Call	0.78
E-mail	0.92
Science collaboration	0.92
E. Coli Metabolism	0.96
Yeast Protein Interactions	0.88
LN	0.00535

Figure 7: Random failures in networks. Values of critical thresholds for other real networks are taken from [1].

3.2 Targeted attacks

Targeted attacks on LN nodes are also a major concern as the short history of LN has already shown it. On 2018 March 21st [2], 20% of nodes were down due to a Distributed Denial of Service (DDoS) attack against LN nodes. Denial of Service (DoS) attacks are also quite probable by flooding HTLCs. These attack vectors are extremely harmful, especially if they are coordinated well. One might expect that not only state-sponsored attackers will have the resources to attack a small network like LN. In the first attack scenario we removed 30 highest-degree nodes one by one starting with the most well-connected one and gradually witdhraw the subsequent high-degree nodes. We recorded the number of connected components. As it is shown in Figure 8. even just removing the highest-degree node[3] fragments the LN graph into 37 connected components! Altogether the removal of the 30 largest hubs incurs LN to collapse into 424 components.

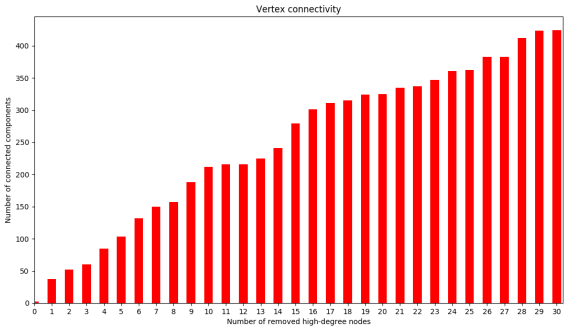


Figure 8: LN's vertex connectivity, when all the 30 largest hubs are removed one by one

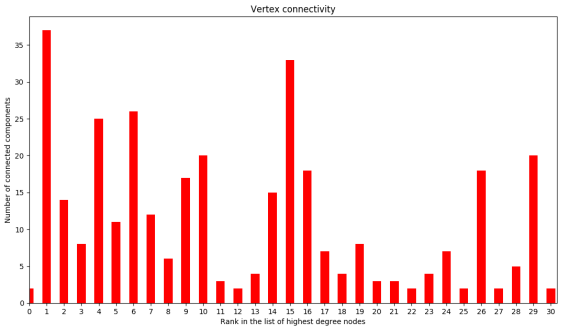


Figure 9: LN's vertex connectivity if only one high-degree node is removed from the graph.

[2] https://www.trustnodes.com/2018/03/21/lightning-network-ddos-sends-20-nodes
[3] http://rompert.com/

We reasserted the targeted attack scenario, but for the second time we only removed one of the 30 largest hubs and recorded the number of connected components. As it can be seen in Figure 9 most of the hubs (25!) are so critical that their removal would be catastrophic for LN, namely they would leave behind several disconnected components.

Such network fragmentations are unwanted in case of LN, because they would make payment routing substantially more challenging (one needs to split the payment over several routes) or even impossible (there would be no routes at all). An analogous dissolution would effectively render LN non-functional.

3.3 Fixing LN's resilience against random failures and attacks

Designing networks which are robust to random failures and targeted attacks appear to be a conflicting desire [1]. For instance a star graph, the simplest hub and spoke network, is resilient to random failures. The removal of any set of spokes does not hurt the connectedness of the main component. However it can not withstand a targeted attack against its central node, since it would leave behind isolated spokes.

Nonetheless, we could still enhance the network's attack tolerance by connecting its peripheral nodes [1] and mandating newcomers to connect to not only hubs as current implementations do but also to at least a few random nodes. This would envolve that even the removal of major hubs would leave the connectedness of the major component intact.

4 Privacy

topological anomalies have privacy implications, low usage of tor, even tor can not help

5 Conclusion

Shiny figures of LN's topology, like Figure 1, convey only false sense of security and robustness.

6 Acknowledgements

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