Network Analysis of the Lightning Network

Ivan Gallo Marina Ribaudo Matteo Dell'Amico

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The Lightning Network (LN) [1] is a Layer 2 payment protocol built atop Bitcoin which facilitates rapid transactions between participating nodes, offering a potential remedy to Bitcoin's scalability challenge. Leveraging smart contracts to establish *payment channels* between parties, the LN enables cost-effective transactions compared to on-chain Bitcoin (slow) transactions.

Several are the research questions we can ask in this context, many of them with no definitive answer, for example:

1. How big is the Lightning Network?
2. How does it evolve?
3. Is there a correlation between the value of Bitcoin, the cost of transactions, and the growth of the Lightning Network?
4. How decentralized is the Lightning Network?
5. How stable is it over time?

To answer some of these questions, we have collected periodic snapshots of the network since April 2023. Employing classical network analysis techniques, we will explore the transaction structure within the LN, offering a thorough insight into its topology, centrality, and robustness, including longitudinal studies using a dataset collected for one year. Since the LN is the most promising approach to improve Bitcoin's scalability, we believe our study gives insight into Bitcoin's potential as a global, scalable payment system.

To comprehend the network's structure and capabilities, it is crucial to understand the underlying data structures and fields associated with *nodes* and *channels*. An LN node is characterized by several key *fields* that provide essential information about the node's identity, connectivity, and supported features. For instance, the `features` field lists the features supported by the software. Features are key-value pairs; the value consists of the feature's name, whether the node requires it, and whether it is a known feature. For example, the `amp` feature corresponds to Atomic Multi-Path Payments, e.g., a single payment can be split across multiple paths within the LN, enhancing the reliability and flexibility of routing payments, especially in scenarios where individual channels may have insufficient capacity.

Examples of analysis

Using a Python tool we developed we can perform several analyses to investigate the topology of the network, its centrality, robustness, and other relevant metrics. Due to the lack of space, we will introduce only a few examples of the results we can obtain using a single snapshot.

Network	**Lightning Network**	**Giant Component**
Graph type	Directed Multigraph	Directed Multigraph
Number of nodes	19,788	19,121 (96.63%)
Number of edges	80,527	75,064 (93.25%)
Diameter	—	13
Number of triangles	159,034	
Density	$\simeq 0.00041$	
Assortativity	$\simeq -0.148$	
Average degree	8.1	
Average clustering coefficient	$\simeq 0.114$	
Number of components	309	

Table 1: Some Lightning Network graph statistics and measures.

The statistics in Table 1 provide a general understanding of the network's size, density, connectivity, and overall structure. With 19,788 nodes and 80,527 edges, the network demonstrates a considerable degree of interconnectivity; the average degree indicates that each node is connected to approximately 8 others. The system exhibits a disassortative mixing pattern (negative assortativity value of about -0.148) suggesting that nodes with higher degrees—acting as hubs—tend to connect to nodes with lower degrees serving as spokes. The existence of such hubs can imply that transaction routing and fee negotiation power are concentrated within a subset of nodes. Monitoring centralization tendencies is essential to ensure a fair and decentralized network aligned with the fundamental principles of blockchain technology.

Not all nodes are directly connected, hence intermediaries or hubs are necessary to route transactions. The sparse nature of the network can be attributed to various factors, such as limitations on available liquidity or participants' preferences for specific routing paths. While this may introduce additional hops and potentially increase transaction latency, it enables handling a larger volume of transactions efficiently. Using indirect payment channels and routing through well-connected hubs allows participants to transact with nodes they do not have direct connections with, thus enhancing the scalability and flexibility of the network.

The network is not fully connected, consisting of 309 connected components. These components represent distinct sub-networks within the system, with no connectivity between them. With approximately 96.63% of the total nodes and 93.25% of edges, the giant component includes almost all the participants and channels, with the only exclusion of small clusters and communities. The giant component has a diameter of 13 (i.e., the maximum shortest path between any two nodes within this subgraph is 13 hops). The presence of such a well-connected giant component enhances the network's robustness, as failures of non-hub nodes are less likely to disrupt the overall transaction flow.

Table 2 shows the number of nodes with a certain degree and the frequency with which they appear. Looking at the data values it is possible to observe that most nodes have degrees equal to 1 or 2, being connected only to a single or two hubs and not participating in the transaction routing process (long-tail pattern). The two most connected nodes have respectively 3,689 and 2,391 channels. Navigating the snapshot data and looking at the associated public keys of the two nodes, it is also possible to collect the node aliases, in order: `ACINQ` [2], a company working on Bitcoin scalability and LN development and maintenance, and `WalletOfSatoshi.com` [3], a service allowing users to send and receive payments easily.

Degree	N^o of nodes	Freq.
1	7,998	40.42 %
2	3,409	17.23 %
3	1,902	9.61 %
4	1,150	5.81 %
5	850	4.30 %
6	619	3.13 %
7	476	2.40 %
8	350	1.77 %
9	328	1.66 %
10	275	1.39 %
11–20	1,199	6.06 %
21–50	807	4.08 %
51–100	239	1.21 %
101–500	162	0.82 %
501–1,000	14	0.07 %
1,001–2,000	7	< 0.04 %
2,001–3,000	1	< 0.01 %
3,001–4,000	1	< 0.01 %

Table 2: LN degree distribution.

Pos	Degree	PageRank	Betweenness
1	ACINQ	ACINQ	ACINQ
2	WalletOfSatoshi.com	LNBiG[lnd-41/old-lnd-27]	WalletOfSatoshi.com
3	1ML.com node ALPHA	CryptoChill	Kraken
4	CoinGate	WalletOfSatoshi.com	CoinGate
5	Kraken	spikeandstar	Boltz
6	ln.nicehash.com	TheBebop	ln.nicehash.com
7	Boltz	LNBiG.com[lnd-20]	BCash_Is_Trash
8	bfx-lnd0	Lightning.Watch	deezy.io
9	deezy.io	gameb_2	OpenNode.com
10	OpenNode.com	mojbitcoin.sk	Voltage-c1

Table 3: Top 10 nodes according to different centrality measures.

Table 3 presents the names of top-ranking nodes according to various centrality measures. Certain nodes consistently appear in multiple centrality rankings; this highlights their importance in maintaining network resilience, facilitating efficient transactions, and enhancing overall network efficiency. The price to be paid is some form of centralization, these nodes being crucial but—at the same time—critical single points of failure.

Further research can provide more insights into the dynamic behavior of the LN over time, contributing to the development of strategies to optimize network performance, improve transaction routing algorithms, and enhance overall scalability.

References

[1] Joseph Poon and Thaddeus Dryja. The Bitcoin Lightning Network: Scalable Off-Chain Instant Payments, 2016. Last accessed: April 2024. URL: `https://lightning.network/lightning-network-paper.pdf`.

[2] ACINQ | A Bitcoin Technology Company. URL: `https://acinq.co/`.

[3] Wallet of Satoshi — The World's Simplest Bitcoin Lightning Network Wallet. Last accessed: April 2024. URL: `https://www.walletofsatoshi.com/`.