# Mass Exit Attacks on the Lightning Network

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#### **ABSTRACT**

The Lightning Network (LN) has enjoyed rapid growth over recent years, and has become the most popular scaling solution for the Bitcoin blockchain. The network consists of payment channels that hold different amounts of BTC in their capacity. The security of the LN hinges on the ability of the nodes to close a channel by settling their balances, which requires confirming a transaction on the Bitcoin blockchain within a pre-agreed time period. This inherent timing restriction that the LN must satisfy, make it susceptible to attacks that seek to increase the congestion on the Bitcoin blockchain, thus preventing correct protocol execution.

We study the susceptibility of the LN to *mass exit* attacks, in the presence of a small coalition of adversarial nodes. This is a scenario where an adversary forces a large set of honest protocol participants to interact with the blockchain. We focus on two types of attacks: (i) The first is a *zombie* attack, where a set of *k* nodes become unresponsive with the goal to lock the funds of many channels for a period of time longer than what the LN protocol dictates. (ii) The second is a *mass double-spend* attack, where a set of *k* nodes attempt to steal funds by submitting many closing transactions that settle channels using expired protocol states; this causes many honest nodes to have to quickly respond by submitting invalidating transactions.

We show via simulations that, under historically-plausible congestion conditions, with mild statistical assumptions on channel balances, both of the attacks can be performed by a very small coalition. For example, a coalition of just 30 nodes could lock the funds of 31% of the channels for about 2 months via a zombie attack, and could steal more than 750 BTC via a mass double-spend attack, if the *watchtowers* algorithms do not make use of sophisticated strategies.

To perform our simulations, we formulate the problem of finding a worst-case coalition of k adversarial nodes as a graph cut problem. Our experimental findings are supported by a theoretical justification based on the scale-free topology of the LN. We emphasize that the proposed attacks should not be considered as an issue of the protocol design, but rather as an inherent issue of payment channels network without general computability on layer-1.

#### **CCS CONCEPTS**

• Security and privacy  $\rightarrow$  Distributed systems security.

## **KEYWORDS**

Blockchains, Bitcoin, Lightning Network, Layer 2, Blockchain Scalability

#### 1 INTRODUCTION

The Lightning Network (LN) [17] is emerging at the most popular layer-2 scaling technology for Bitcoin. We model the LN by a graph G; every vertex can be assumed to be a user and every edge is a bi-directional payment channel between two nodes<sup>1</sup>.

The LN is implemented via a cryptographic protocol executed by the nodes. Effectively, pairs of nodes implement a payment channel that allows them to exchange promises to pay a certain amount to each other. These promises are valid, as long as they are redeemable on layer-1, i.e. the Bitcoin blockchain. The LN is permissionless, that is, any user can join the protocol pseudonymously. Therefore, users can have arbitrarily adversarial behavior, so the LN must be able to handle byzantine failures. This implies that each node in a channel  $e \in E(G)$  must be able to unilaterally close e by performing layer-1 transactions. However, in order to prevent double-spend, the protocol must prohibit a node from closing a channel using a layer-1 transaction from an earlier state of the channel. This implies that each closing transaction,  $e \in E(G)$ , must come with a delay,  $D_e$ , measured in block height, that is chosen during the creation of the channel e by the two participating nodes. Specifically, suppose that a node, u, broadcasts its intention to unilaterally close a channel,  $e = \{u, v\}$ , by confirming on the blockchain a transaction,  $\tau$ , that corresponds to an old state of e. Then, the node v can get all the funds in the channel by confirming a transaction,  $\tau'$ , that effectively proves that  $\tau$  has expired, within a time window of  $D_e$  blocks since the confirmation of  $\tau$ .

#### 1.1 The attacks

The above inherent timing limitations of the LN protocol renders it susceptible to attacks that try to force a mass-exit event that violates the delay bounds of many edges, thus forcing a deviation from the intended protocol behaviour.

We study the following two attacks of this type, that are performed by an adversary that controls a small coalition of k nodes:

**(1) Zombie attack:** The adversary controls a set of k nodes,  $Z \subseteq V(G)$ , that hold exactly one side of many channels; that is,  $E' = E(G) \cap (Z \times (V(G) \setminus Z))$ . The adversary renders all channel in E' unresponsive, simply by not participating in the protocol. This can be implemented either when Z is a coalition of adversarial nodes, or when an eclipse-type attack (see, e.g. [10, 13]) is performed on all nodes in Z. This forces many honest nodes to submit layer-1 channel closing transactions. We show experimentally that under realistic layer-1 congestion conditions the zombie attack can cause a significant amount of funds to be locked for a large window of time. This deviates from the protocol which attempts to

 $<sup>^1\</sup>mathrm{We}$  omit private channels and focus on publicly known ones that are broadcasted in the peer-2-peer (p2p) layer of the LN.

impose a much smaller delay, *D*, for closing a channel. This attack is similar to the *griefing attack*: the user is forced to broadcast a transaction on Bitcoin Layer 1 to unilaterally close the channel, and potentially pay a high fee due to the congestion generated by the attack. This is an attack that does not aim at stealing funds, but rather to "vandalize" both layer-2 (unusable channels) and layer-1 (congestion). The attack also causes an implicit monetary cost due to the loss of income from serving LN payments during the period the funds are locked.

(2) Mass double-spend attack: The adversary again controls Z as in the zombie attack (in contrast to the zombie attack, for a mass double-spend attack it is not enough to simply eclipse Z). The adversary attempts to perform multiple double-spends by submitting closing transactions for all channels in E' that correspond to earlier states of the protocol. The honest nodes that monitor the blockchain respond by submitting disputing transactions on the blockchain, as soon as any offending transaction is confirmed. The adversary succeeds in stealing the funds when an honest disputing transaction fails to get confirmed on the blockchain before the delay *D* has passed. We experimentally show that, under realistic congestion conditions, if the watchtowers algorithms monitoring the blockchain are not configured correctly, the adversary can succeed in stealing significant amounts of funds.

#### 1.2 Our main results

Informally, our main findings can be summarized as follows.

- Susceptibility to vandalism by a small coalition: We demonstrate experimentally that the zombie attack can be used to lock a significant amount of funds for long periods of time. Our simulations are performed under historically-plausible congestion conditions. The attack succeeds in forcing the funds of honest protocol participants to be locked for a duration that is much longer than the intended upper bound. A detailed exposition of our findings is given in Section 4.
- Incentive-incompatibility in the presence of a small coalition: We demonstrate experimentally that, assuming an adversarial coalition of k = 30 nodes, and under a plausible model for the expected profit of the adversary, the LN is not incentive compatible. Our simulations are performed on a current LN topology, under historically-realistic congestion conditions, and assuming a realistic watchtower algorithm. Our mathematical modeling makes mild statistical assumptions on channel balances. The full details of our mathematical modeling are given in Section 2, and our experimental findings are presented in Section 5. We demonstrate experimentally that with the current LN topology, under historically-realistic congestion conditions, using a realistic watchtower algorithm, under mild statistical assumptions on channel balances, and assuming a coalition of at most k = 30 nodes, the LN protocol is not incentive-compatible. In fact, under reasonable model parameters, the adversarial coalition has a strategy for stealing funds from the honest

protocol participants, with an expected profit of more than 750 BTC. In this case, clearly there is a simplification since we are considering that the coalition of attackers has nothing to lose from the attack, or at least that the business of the attackers has a volume that is less than the expected profit of the attack. Nonetheless, we believe that the trustless nature of the network is questioned by the possibility to perform these attacks. We emphasize that our results doe not imply that  $any\ k$ -coalition can perform this strategy, but rather that such a k-coalition exists and can be computed efficiently in practice.

# 1.3 Theoretical justification

Our experimental findings outlined above suggest that the LN is potentially susceptible to mass exit attacks by a small coalition of adversarial nodes. This phenomenon can be explained by the topological properties of the graph G of the LN. In particular, it has been recently observed that G is scale-free, and follows a power-law degree distribution [14]. This is to be expected due to the complex social dynamics that lead to the formation of G. It has been shown in [7] that in power-law degree graphs, by splitting the nodes into sets of high and low degree,  $V(G) = V_{\text{high}} \cup V_{\text{low}}$ , we obtain a nearly-optimal max-cut. In fact, this is true even for very small sets  $V_{\text{high}}$  (depending on the power-law exponent; see [14] for precise bounds). As we explain in Section 2, for our attacks this implies that if the adversary controls  $Z = V_{\text{high}}$ , then both attacks can be performed effectively by targeting all the channels between  $V_{\text{high}}$  and  $V_{\text{low}}$ .

The above observation implies that the effects of the attacks that we study should be expected to get *worse* for large sizes of the LN, in the following sense: the worst-case k-coalition, for the *same size*, k, can cause more damage in a larger network (either by causing higher total delay in closing channels, or in total funds stolen, depending on the attack).

## 1.4 Organization

The rest of the paper is organized as follows. In Section 2 we show how both the zombie and the mass double-spend attacks can be modeled mathematically so that the problem of selecting a k-coalition of adversarial nodes that maximizes the efficiency of the attack, can be expressed as a variant of the Max-Cut problem. We also present a simple greedy heuristic for solving this problem. In Section 3 we discuss the main statistical assumptions for our simulations. Section 4 presents our experimental results on the zombie attack. Section 5 presents our experimental results on the mass double-spend attack. In Section 6 we discuss possible measures for mitigating the attacks. Section 7 reviews related work. We conclude in Section 8.

# 2 SELECTING AN ADVERSARIAL COALITION AS A GRAPH CUT PROBLEM

We now describe our methodology for choosing an adversarial k-coalition, i.e. a coalition of k nodes. To that end, we first formulate an auxiliary graph-cut combinatorial optimization problem. We then explain how this problem can be used to compute near-optimal coalitions.

## 2.1 The graph cut problem

In a graph, G, a k-lopsided cut is a bipartition,  $(Z,V(G)\setminus Z)$ , of V(G), with |Z|=k. The k-Lopsided Max-Cut problem (k-LMC) is defined as follows. The input consists of a graph G and some  $k\in\mathbb{N}$ , and the goal is to find a k-lopsided cut,  $(Z,V(G)\setminus Z)$ , maximizing the number of edges in the cut, i.e.  $|E(Z,V(G)\setminus Z)|$ . Similarly, in the k-Lopsided Weighted Max-Cut problem (k-LWMC), the input consist of a graph, G, with non-negative edge capacities, and some  $k\in\mathbb{N}$ , and the goal is to find a cut maximizing the total capacity of the edges in the cut, i.e.  $\sum_{e\in E(Z,V(G)\setminus Z)}c(e)$ , where c(e) denotes the capacity of e.

# 2.2 From graph cuts to mass exit attacks

2.2.1 From k-LMC to zombie attacks. The problem of computing a worst-possible k-coalition  $Z \subseteq V(G)$  of adversarial nodes to perform the zombie attack is precisely the problem of computing a k-LMC in G. This is because any edge can be attacked precisely when exactly one of its endpoints is in the adversarial coalition (an adversary cannot attack itself, and an honest node cannot attack another honest node). Moreover, the effectiveness of a zombie attack is maximized when the average delay to close a channel is maximized. This occurs when the number of channels under attack, i.e. the number of edges in the cut, is maximized.

2.2.2 From k-LWMC to mass double-spend attacks. We now argue that, under mild assumptions, the problem of computing a worst-possible k-coalition of adversarial nodes to perform the mass double-spend attack, can be reduced to the problem of solving k-LWMC on G. For any channel  $e = \{u, v\} \in E(G)$  under attack, fix an orientation (u, v) such that  $u \in Z$ , and  $v \notin Z$ ; let  $b_t(e) \in [-c(e), c(e)]$  denote the balance of channel at time t; in particular,  $b_t(e) = \alpha$  when at time t node t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of the capacity of t and t owns t of t or t owns t of the capacity of t and t owns t of t owns t or t or t or t owns t or t or t or t owns t or t or

The quantity  $b_t(e)$  as a function of t is difficult to model and to predict during the attack. This is a challenge for our modeling because the amount of funds that the attacker can steal from a channel depends on the current balance. We avoid the issue of estimating  $b_t(e)$  by introducing a mild technical assumption. Suppose that the adversary participates honestly in the protocol for some amount of time before the attack begins. Let e be some channel where the adversary controls exactly one of its endpoints. Assuming that funds in the LN are allocated efficiently, it follows that in any long enough window of time, we expect to observe times t and t' where  $b_t(e) \ge c(e) - \varepsilon$ , and  $b_{t'}(e) \le -c(e) + \varepsilon$ , for any  $\varepsilon > 0$ . This is because, otherwise, we could remove some of the capacity in e and still be able to route the same set of LN transactions, which would violate capital efficiency. Before the attack begins, the adversary participates in the protocol honestly. During this period, for all of its channels, the adversary collects closing transactions that give almost all the funds to the adversary.

When the attack begins at time t, the adversary stops participating in the LN protocol. Thus, the balances of all channels under attack remain fixed throughout the duration of the attack. By the above discussion, it follows that if the adversary succeeds in stealing the funds from a channel, e, then the adversary profits a total of at least  $c(e) - b_t(e) - c(e)/2 - \varepsilon = c(e)/2 - b_t(e) - \varepsilon$ , where the -c(e)/2 term accounts for the cost of creating the channel. On the

other hand, the adversary fails to steal the funds of channel e precisely when an honest node manages to get the justice transaction confirmed before the expiration; when this happens, the adversary gets penalized by losing all the funds in the channel, thus the adversary gains -c(e)/2, due to the cost of creating the channel. In practice, we first assume that attacked channels are equally funded by both parties. We believe that this can be considered a reasonable assumption, since dual funding has been implemented by one of the major LN client implementations [2].

Unfortunately, the balances of the channels are not publicly known. There has been some work on estimating balances [5, 20], but it is not clear how to model them accurately. In addition, since we cannot probe channel balances because we make use of historical data in our simulations. Moreover, it is possible for the two participating nodes to contribute different amounts of capacity during channel creating. For these reasons, we make the following simplifying assumption:

**Assumption 1:** For any channel e, conditioned on the adversary successfully stealing the funds from e, the expected profit of the adversary is at least c(e)/2.

In particular, Assumption 1 holds if we assume that at the time of channel creation  $t_0$ , we have  $b_{t_0}(e) = 0$ , and that for the time that attack happens, t, we have  $\mathbf{E}[b_t(e) = 0]$ , and setting  $\varepsilon = 0$ .

To support Assumption 1, we performed a brief analysis of the nodes in 30-LWMC: they are well-connected nodes (in terms of number of open channels), and most of them seem to be sellers of inbound liquidity, routing nodes, exchanges, and wallet providers. This empirically supports the validity of Assumption 1: if a lot of the nodes in the attacker coalition, for example, sell liquidity, this means that they open channels with their customers, and then the customers use these channels in order to get paid to sell goods or services. Therefore, the coalition of attackers would have a favorable commitment (i.e., the first one), since they opened the channel providing the liquidity, but it is expected that, over time, these channels will be used in order to acquire services, so the balance of the channels will eventually go to the victim node.

The total profit of the adversary depends on the probability of stealing the funds of any channel *e*. To that end, it is reasonable to assume that all honest nodes use the same strategy. Therefore, by symmetry, we arrive at the following assumption:

**Assumption 2:** There exists some p > 0 such that for all  $e \in E(G)$  under attack, the adversary succeeds in stealing the funds from e, independently, and with probability p.

Let  $P_e$  denote the profit that the adversary makes by attacking e, and let  $P = \sum_e P_e$  be the total profit of the adversary. By Assumptions 1 & 2 and the linearity of expectation, we get that  $\mathbf{E}[P] = \sum_{e \in E(Z,V(G) \setminus Z)} \mathbf{E}[P_e] = \sum_{e \in E(Z,V(G) \setminus Z)} (p-1/2) \cdot c(e) = (p-1/2) \sum_{e \in E(Z,V(G) \setminus Z)} c(e)$ . In other words, the expected profit of the adversary is equal to the total capacity of the computed cut, times a scaling factor of p-1/2. The following summarizes the above discussion.

PROPOSITION 2.1. Under Assumptions 1–2, for any p > 1/2, the mass double-spend attack is profitable in expectation. Moreover, the k-coalition that maximizes the profit of the adversary is precisely an optimal solution to k-LWMC.

## 2.3 Computing lopsided max-cuts

Since the k-LMC problem is a generalization of Max-Cut, it follows that it is also NP-hard [12]. Perhaps surprisingly, the generalization of Max-Cut that we consider does not appear to have been studied in this precise form previously.

We observe empirically that a simple greedy algorithm computes very good solutions. The greedy algorithm is as follows. We start with the cut  $(\emptyset, V(G))$ , that contains all vertices on the right side. For k steps we repeat the following. We greedily pick the vertex on the right side to move to the left side, maximizing the total capacity of edges in the cut.

We compared this greedy algorithm with the implementation of approximate max-cut solver in the Neo4j *Graph Data Science* library, which uses a greedy randomized adaptive search procedure parallelized (GRASP) style algorithm [3]. When taking the maximum over all  $k \in \{1, \ldots, |V(G)|-1\}$ , the simple greedy algorithm we consider outperforms the results of the Neo4j library. For this reason, we have chosen the simple greedy algorithm for our experiments. We remark, however, that obtaining a better solver for k-LMC and k-LWMC can only strengthen our results, since better solutions directly improve the effectiveness of our attacks.

The values of the solutions for k-LMC and k-LWMC that we computed using the greedy algorithm, as a function of k, are presented in Figure 1. We remark that the global solution that we compute for Max-Cut contains OPT = 63251 edges. Similarly, the best solution computed for weighted Max-Cut has total capacity of OPT<sub>W</sub> = 2464.37 BTC, while covering 58531 edges. The results on the greedy solutions for k-LMC and k-LWMC that we obtained are presented in figure 1. Table 1 gives the solutions for some representative values of k, related to k-LWMC. We observe that even for very small coalition size, k, there exist solutions that are close the global optimum. For example, even with k = 30 nodes, the adversary can attack a number of channels that is 31% of the global max-cut, which is 23% of all channels in the network.

This phenomenon agrees with the behavior expected from the theory of scale-free networks, as discussed in the previous Section.

k	capacity in BTC (% of $OPT_W$ )	# edges (% of OPT)
10	1199.89 (48.69%)	10911 (17.25%)
30	1685.13 (68.38%)	20084 (31.75%)
100	2107.70 (85.53%)	35447 (56.04%)
300	2312.47 (93.84%)	44522 (70.39%)

Table 1: Result on the greedy solutions computed for k-LMC and k-LWMC on the LN graph G.

#### 3 THE EXPERIMENTAL SETUP

We now describe the modeling of the LN used in our experiments. The graph G of the LN used in our experiments is obtained using the lnd lightning node implementation. The snapshot of the network that we use was taken on May 2022, and contains n = |V(G)| = 17813 nodes and |E(G)| = 84927 channels.

## 3.1 Modeling layer-1 congestion

The effectiveness of the attacks we consider depends on the confirmation times of the transactions performed by the adversary and the honest nodes. Therefore, the results depend on the congestion on the Bitcoin blockchain during the attack.

One way to estimate confirmation times is to use statistical models, such as [8]. However, this approach requires estimating the parameters of the models involved, which can introduce bias on the results. For this reason, we decide to perform simulations using historical data on the Bitcoin mempool <sup>2</sup>.

All of our simulations are performed under two different congestion scenarios:

**Scenario 1:** The attack starts on Dec. 7, 2017 at 08:15 (CDT), which marks the beginning of a period of high congestion. **Scenario 2:** The attack starts on Jan. 1, 2022 at 00:00 (CDT), which is during a period of typical congestion.

Scenario 1 represents a worst-case situation for the victims, since the attack takes place during a period of high congestion on layer-1. The data used to run the experiments was obtained from [11], with a snapshot taken every minute regarding the number of transactions in the mempool for a number of predefined fee ranges. Figure 2 depicts the congestion during the selected period. The mempool congestion in the selected period lasted approximately until the end of January (about 8000 blocks).

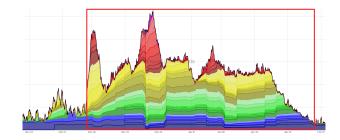


Figure 2: Levels of congestion between December 2017 and February 2018, showing the end of the period of congestion that started around Dec. 6, 2017. Different lines represent number of transactions for different fee ranges in the mempool, with blue and green lines representing lower fee transactions, and so on. The red square represents approximately the time window considered for experiments.

## 3.2 Modeling the strategy of honest nodes

In both of the attacks presented in this paper, we consider two different strategies for the honest players:

• Static strategy: In this case, all honest nodes use a fixed fee when transmitting their transactions. This is the optimistic case for the adversary, since it is harder for honest players to get their transactions confirmed during periods of high congestion.

 $<sup>^2{\</sup>rm The}$  code implementing the simulations and the experiments can be found at the following URL: https://drive.google.com/file/d/1jPZHvm2OCovhKUHso6TkPvmJM89vQS5F/view?usp=sharing

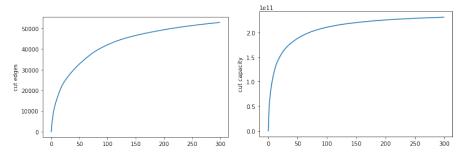


Figure 1: The value of the greedy solutions for k-LMC (left) and k-LWMC (right), as a function of k.

• *Dynamic strategy*: The honest nodes increase the fee of their transactions until they get confirmed or the delay expires. The rate of increase is controlled by three parameters: The initial fee, the *step* parameter, t, and a parameter  $\beta > 1$ . Every t blocks, any honest node increases the fee of any pending transaction via the replace-by-fee (RBF) mechanism, by multiplying its fee by  $\beta$ . Therefore, the fees increase exponentially.

The dynamic strategy requires some considerations regarding the various type of on-chain transactions that both the attacker and the victims have to broadcast. First of all, justice transactions only require honest nodes' signature, therefore RBF can be used, and the dynamic case is feasible in the mass double-spend attack. In the zombie attack, the fee increase is related to channel force-closing transactions: channel commitments are signed by both parties when the commitment is created, therefore in general the fee is static and decided when the transaction is signed. However, with the implementation of anchor output-based channels [1], the fee of forceclosing transactions can be bumped, therefore the dynamic strategy of honest nodes can also be implemented during the zombie attack. In the zombie attack, if the strategy is static, the fee will remain the same for all the duration of the simulation, until all the zombie channels have been closed. When the dynamic strategy is employed, the fee will be increased every t blocks, for all the transactions that are still unconfirmed. For example, if step = 2, then every 2 blocks the fee related to unconfirmed zombie channels' closing transactions will be bumped. In the mass double-spend attack, honest nodes' transactions are submitted as soon as the corresponding malicious transaction is confirmed (effectively simulating the behaviour of watchtowers). The initial fee for victims' justice transactions is set as the average fee at the moment of submission. After submission, fee increments in the dynamic scenario follow the same mechanism as in the zombie attack simulation.

# 4 RESULTS ON THE ZOMBIE ATTACK

# 4.1 Outline of the experiments

The simulation of the zombie attack works as follows.

- (1) At the beginning of the simulation, there are *n* zombie channels that must be closed. These would typically be the channels in the solution to *k*-LMC.
- (2) We compute the number of transactions contained in any new block from historical blockchain data. For example, in

- scenario 1, since the time window starts on Dec. 7, 2017 at 08:15 (CDT), the first block that will be mined is the block #498084<sup>3</sup>.
- (3) We check if there is enough space in the block for any transaction by counting the number of transactions in the mempool with a higher fee (also considering transactions which were already in the mempool with the same fee rate as our closing channel transactions).
- (4) If the block can fit some of our closing channel transaction, we remove them from the remaining number of zombie channels to be closed.
- (5) When we reach a state in which all the LN channel closing transactions have been confirmed, the simulation ends.

In the results we do not consider the delay set at channel opening (to\_self\_delay). However, as we will see in section 5.2.2, an average delay can be considered to be about 500 blocks.

# 4.2 Results

4.2.1 Static Case. Figure 3 shows the number of remaining zombie channels to be closed as a function of time (measured in blocks) elapsed during the simulation, for various fees used by honest nodes (that are fixed since we are in the static case). The results in the high congestion situation is consistent with respect to the duration of the congestion: when the fee is less than 50 sat/vByte, all transactions tend to be confirmed at approximately the same time as congestion decreases significantly (around the 8000th block from the beginning, just under two months). This implies that the bottleneck is caused due to the congestion in the mempool. In the same figure, in the middle it is possible to notice that, even for small coalition sizes, the zombie attack causes high delay. Actually, the difference between attacking MC and 30-LMC is not much pronounced: this is caused by the fact that in this case the layer-1 congestion is not dominated by LN transactions, but rather by standard transactions that were in the mempool in the analyzed time window.

For Scenario 2 (low congestion), in Figure 3 we observe that the delays to close a channel are significantly smaller.

Figure 4 depicts the number of blocks needed to close all the zombie channels as a function of the fee used by the victims for the closing channel transactions, for different values of k. We observe that even when attacking only a few nodes (k = 10), the attacker cause a lot of damage to users in terms of time their funds are locked,

<sup>&</sup>lt;sup>3</sup>https://www.blockchain.com/btc/block/498084

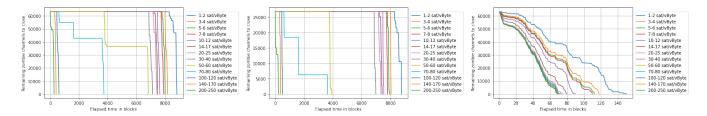


Figure 3: Number of remaining Zombie channels to be closed as a function of time measured in blocks, for various fee ranges, with static honest player strategy, in Scenario 1 (attacking the total LMC on the left and 30-LMC on the middle) and Scenario 2 (attacking the total LMC, on the right).

when the congestion is high. The number of blocks that victims need to wait in order to unlock their funds varies significantly based on the fee used to close the channels. In fact, users are forced to pay a high fee of about 100 sat/vByte to redeem funds before two weeks ( $\approx$  2000 blocks) since the moment of the attack.

4.2.2 *Dynamic Case.* In the dynamic case, the fees used by victims of the attack can increase over time (using RBF) in response to a delay in the confirmation of the transactions. We consider  $\beta = 1.01$ , so in every bump the fee increases by 1%, and various step values.

Figure 5 depicts the number of blocks needed to close all the zombie channels, as a function of the parameters of the dynamic strategy. We observe that, even for a coalition of size k=30, if honest users wish to close their channels in significantly less that 1000 blocks, then either the initial fee must be set high (about 80 sat/vByte), or the fee must be bumped aggressively (at least once every 10 blocks).

Figures 5 and 6 also consider a hypothetical attack with 1 million zombie channels, which corresponds to a much larger graph in a possible future snapshot of the LN.

# 5 RESULTS ON THE MASS DOUBLE-SPEND ATTACK

We now present our results on the mass double spend attack.

# 5.1 Outline of the experiments

The simulation is performed as follows.

- (1) When a new block is minted, we check if some of the LN transactions can be included in the block, counting the number of transactions with a higher fee and checking if this number is less than the number of transactions historically contained in the block at the current index.
- (2) If there is some potential space for LN transactions in the new block, we start by iterating over them: before including them into the block, we check their position in their specific fee range in the mempool. If, at the moment of insertion in the mempool, there were already some transactions with the same fee rate, these transactions would need to be confirmed before those that we are monitoring.
- (3) At the beginning, there are only attacker transactions: we fit as many as we can in the first block that has available space for them. For each confirmed attacker transaction, we submit to the mempool the corresponding victim's justice

transaction. The fee of the justice transactions is computed as the average fee from the mempool data at the moment of submission of the transaction.

We remark that in this case is that, unlike the zombie attack simulation, the victims' justice transactions are submitted at different times and potentially with different fees. Therefore, we must keep track of the position of each justice transaction in the mempool in its fee range, to detect its confirmation block as accurately as possible.

Another detail is that when we decide that, for example, n attacker transactions are included in a block, we are actually replacing n transactions which, if we look at historical mempool data, were removed from the mempool, but in the simulation that we are executing they should still be in the mempool as unconfirmed. For simplicity, in our simulation we consider only the transactions that are directly replaced by LN transactions, and we don't consider the "cascade" of replaced transactions. This is an optimistic assumption for victims because it implies less transactions in the mempool and thus less congestion, therefore it does not weaken our results.

#### 5.2 Results

5.2.1 Static Case. Figure 7 shows the number of justice transactions that get confirmed after the predefined delay (which are therefore unsuccessful in avoiding the loss of funds), in Scenario 1, as a function of the fee paid by the attacker. We observe that, even for large delays (e.g. 1000 blocks), the number of exploited channels is high, especially if the attacker is willing to pay a high fee for its transactions. We also note that, it is not guaranteed that increasing the fee for the attacker leads to better attack outcome, as it is possible to see with a delay of 500 blocks. This is due to the fact that a higher fee also implies that the victim transaction is submitted earlier, and the effect on the attack results depends on the level of congestion in the moment that the each victim transaction is submitted. The level of congestion in the considered time window is not constant, it changes significantly and not monotonically over time: therefore, it could happen that using a higher fee causes victim transactions to be submitted in a moment in which the mempool is less overloaded, hence they can also be confirmed earlier, actually reducing the effect of the attack. Figure 7 also shows consistent results with respect to a low congestion period: a small to\_self\_delay is generally enough to minimize the risks for LN users.

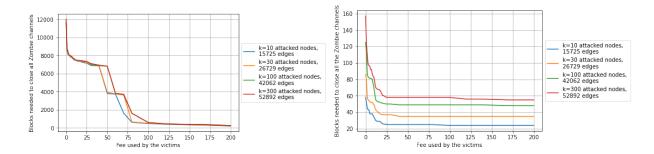


Figure 4: Time measured in blocks needed to close all the channels during a zombie attack, as a function of the fee used by the victims for different number of adversarial nodes (in sat/vByte), with static honest player strategy, in Scenario 1 (left) and Scenario 2 (right).

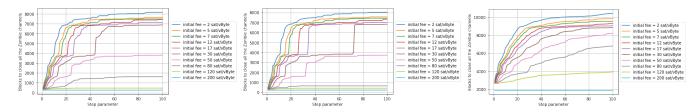


Figure 5: Number of blocks needed to close all the Zombie channels, with dynamic honest player strategy, as a function of the step parameter, with beta=1.01, in Scenario 1, under three different attacks: total LMC (left), 30-LMC (middle), and 1 million channels (right).

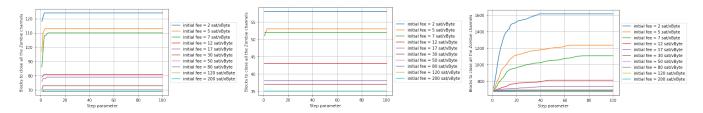


Figure 6: Number of blocks needed to close all the Zombie channels, with dynamic honest player strategy, as a function of the step parameter, with beta=1.01, in Scenario 2, under three different attacks: total LMC (left), 30-LMC (middle), and 1 million channels (right).

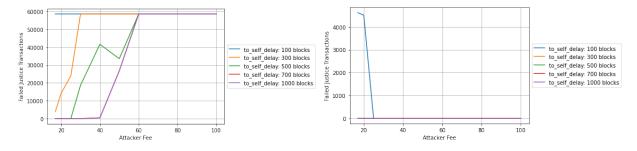


Figure 7: Number of justice transactions that are not able to be confirmed before the to\_self\_delay as a function of the fee used by the attacker (in sat/vByte) for various values of to\_self\_delay with static honest player strategy, in Scenario 1 (left) and Scenario 2 (right), attacking the total LWMC.

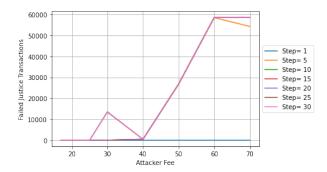


Figure 8: Number of justice transactions that are not able to be confirmed before the to\_self\_delay as a function of attacker fee (in sat/vByte) with dynamic honest player strategy, for various values of the step parameter (Scenario 1), attacking the total LWMC.

5.2.2 References to LN nodes implementation. We now investigate how the most popular LN node implementation currently handles the delay agreed at channel opening, and how this affects our attack. Currently, the most used LN node implementation is LND (Lightning Network Daemon). In the Lightning Network specification (BOLT), to\_self\_delay is the parameter that sets the delay (in blocks) that the other end of the channel must wait before redeeming the funds in case of uncooperative channel closure. LND offers users the option to set a fixed custom value for this parameter in the lnd.conf configuration file (the bitcoin.defaultremotedelay entry). By default, if this parameter is not set, it is handled dynamically and scaled according to the capacity of the channel, with a maximum delay of 2016 blocks and a minimum delay of 144 blocks. With respect to the attack that we are describing, it is interesting to see the effect of the usage of this algorithm to choose the delay. Currently, as of April, 2022, the average capacity of a LN channel is 0.044 BTC <sup>4</sup>. This means that, with the default LND algorithm, a channel of average capacity has

$$delay = 2016 \ blocks \cdot \frac{chanAmt}{MaxFundingAmount} \approx 529 \ blocks$$

According to the LND documentation, MaxFundingAmount is defined the the BOLT-0002 specification and it is a soft-limit of the maximum channel size at a protocol level: it is currently set to  $2^{24}-1$  satoshis. Obviously, in our case chanAmt is set to 0.044 BTC.

For the dynamic case we will make use of the delay computed above (529 blocks).

5.2.3 Dynamic Case. The dynamic case, in which victims are also increasing their fee if the corresponding justice transaction is not confirmed after the number of blocks determined by the *step* parameter, has been implemented and is shown in Figure 8. Similarly to the zombie attack, the study of the dynamic case is useful to propose possible strategies to defend against this type of attacks. As a remark, the curves shown in Figure 8 are not monotonic, because the congestion level in the considered time window is not constant. Since the initial victim's fee is computed as the average fee at the moment of submission to the mempool, and each victim's

transaction is sent when the corresponding attacker's transaction is included in a block, even using an higher fee doesn't necessarily always optimize the attacker's strategy. As a matter of fact, it is possible that using a fee of 40 sat/vByte leads to victims' transactions with an higher initial fee, that allows a greater number of justice transactions to be confirmed on time, with respect to the usage of 30 sat/vByte as the attacker fee.

5.2.4 Considerations regarding the feasibility of the attack. If the attackers' coalition is able to steal funds from all the attacked channels, then there are no costs for the attacker, other than those of transaction fees. Nonetheless, in a realistic setting it is possible that some of the justice transactions submitted by the victims will be confirmed before the expiration of the to\_self\_delay. These transactions will cause a penalty for the attacker, as the balance of the channel will be claimed by the victim. By Assumption 1, for any successfully compromised channel, e, the attacker will gain c(e)/2, in expectation. Therefore, the whole attack is profitable when the attacker steals funds from a set of channels that contain at least half of the total capacity of all channels under attack. The profit of the attacker under different conditions is depicted in Figures 9, 10 and 11. We observe that even with a coalition of k=30 nodes, under heavy congestion, using adversarial transaction fee of 50 sat/vByte, when the honest nodes bump their fee every 3 blocks (i.e. about every 30'), the adversary has total expected profit of more than 750 BTC.

#### **6 MITIGATIONS**

We now discuss potential mitigations for the attacks considered.

## 6.1 Mitigations for Mass Double-Spend Attack

- 6.1.1 Increase to\_self\_delay. As we observed in the simulation results, increasing the to\_self\_delay helps in reducing the damage made by the attack. However, this comes at a high cost in terms of usability: if the other party is unresponsive, an honest user has to wait for that increased delay to be able to recover and use the funds locked in the channel. We note also that this modification would worsen the delay in the zombie attack.
- 6.1.2 Watchtowers. Watchtowers are services that offer protection against fraudulent commitment to prevent funds losses when users are offline. They act in response to a non-valid commitment posted on-chain, by broadcasting a justice transaction as soon as the attacker transaction has been confirmed. The exact parameters of the strategy of the watchtower should be carefully set by the operator: our simulations suggest that during periods of high layer-1 congestion, the watchtowers should bump the fees of unconfirmed justice transactions aggressively.
- 6.1.3 Avoid waiting until the attacker transaction is confirmed. A different watchtower strategy would be to monitor the mempool for adversarial transactions. In this case, when an adversarial transaction is detected in the mempool, the watchtower attempts to frontrun the adversary by submitting a channel-closing transaction with a higher fee.

 $<sup>^4\</sup>mathrm{Data}$  from 1ML.com

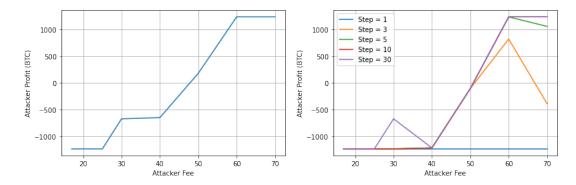


Figure 9: Attacker profits as a function of the fee used by the attack in Scenario 1 (in sat/vByte), attacking all the edges in the weighted Max-Cut in the static case (left) and dynamic case (right), for various values of the step parameter.

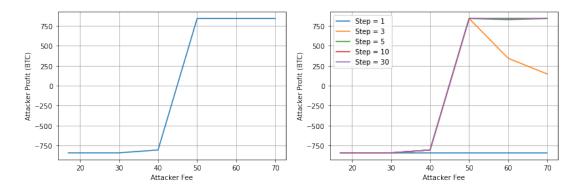


Figure 10: Attacker profits as a function of the fee used by the attack in Scenario 1 (in sat/vByte), attacking 30-LWMC in the static case (left) and the dynamic case (right), for various values of the step parameter.

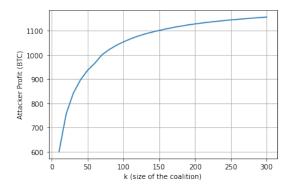


Figure 11: Attacker profits as a function of k parameter, in the dynamic case, with 60-69 sat/vByte as attacker fee, beta=1.01 and step=6.

#### 6.2 Mitigation for Both Attacks

6.2.1 Increased block size. Increasing the block size allows more transactions to be included, and therefore it increases the throughput of the network, reducing the effects of the attacks just described. However, increasing block size decreases decentralization. This is

due to the fact that increasing the block size leads to a higher cost for running a Bitcoin node. Obviously, given the historical implications of such a modification of the layer-1 protocol, this can only be considered as a merely theoretical mitigation technique.

6.2.2 Account-based blockchains. The attacks we consider exploit the fact that the bitcoin blockchain uses UTXOs to keep track of users' funds. If a different blockchain is used, such as Ethereum, where user funds are stored in account balances, then the following mitigation is possible. The payment-channel protocol can use a smart contract for depositing funds during channel creation, and for withdrawing them during channel closing. The same smart contract is used for all the channels in the network. If, within a short time period, honest users prove to the smart contract that several invalid channel closures occurred, then the smart contract pauses channel closures for a specified period of time. This mechanism can be used to pause the network during an attack occurring in high congestion conditions. This solution has the drawback to introduce the risk of griefing-like attacks: a user could open useless channels, and then broadcast past commitments in order to pause channel closures for all the users. To avoid this, the mechanism could be driven by the votes of a DAO instead of an automatic pause, in order to evaluate each case to understand if there is a real attack going on in the network.

6.2.3 Incentivize low-degree nodes. Our attacks can be effective even in the presence of small adversarial coalitions. This is because the LN network has a power-law degree distribution, which implies that there exists large k-LMCs and k-LWMCs, for small values of k. If LN routing algorithms were to give priority to paths that use low-degree nodes, then it is reasonable to expect that that degree distribution of the LN would become closer to uniform, and thus the sizes of the maximum k-LMCs and k-LWMCs should decrease. This would render both attacks less effective, for the same coalition size. However, it is unclear how this modification would affect the routing properties of the LN.

#### 7 RELATED WORK

LN attacks which exploit layer-1 congestion have already been described in the literature: [9] presents the *Flood & Loot* attack. This attack makes use of HTLCs and multi-hop payments: the attacker controls two nodes that are not directly connected, the source and the target. The paths between them are flooded with a high number of low-value HTLC payments from the source to the target. When all the HTLC payments have been completed, the source node refuses to resolve the payments with the first node in the payment path, which is the victim. The victim is therefore forced to unilaterally close the channel, since the source node is unresponsive. The high number of unresolved HTLCs and the consequent congestion on layer-1 cause some of the victim transactions not to be confirmed in time, allowing the attacker to steal some of the funds. The exploited mechanisms partially differ from those used by the attacks presented in this paper, since we do not make use of multi-hop payments, but rather direct channels between nodes. An interesting property of this attack is that it causes a lot of congestion on layer-1 with low cost for the attacker: therefore it is possible to use it to amplify the effects of zombie attacks and mass double-spend attacks.

Similar results obtained in [16]: however, in this work they target the entire network, and an attack that is similar to the zombie attack is described. A greedy algorithm is designed to select the channels to be flooded in order to maximize the locked capacity. This is also similar to what is proposed in [19], where they analyze attack strategies by making use of the topological properties of the LN: for example they present some strategies to choose nodes to be removed for partitioning attacks. They propose strategies such as removing nodes by decreasing degree, by decreasing betweenness and eigenvector centrality, and by highest ranked minimum cuts. This is similar to our strategy for selecting an adversarial coalition for the zombie attack, but with a different objective.

A well-known attack on the LN is the *griefing attack* [15]. In this case the attacker saturates HTLC multi-hop payments path, and makes the channels that constitute the path unusable for new payments. The corresponding channels must be force-closed on-chain, therefore the victims' funds are locked for the delay specified at channel creation. In general, griefing attacks do not aim to steal funds, but users are forced to pay high fees to close the channels in a small number of blocks. Moreover, layer-2 is disrupted since potentially many channels are out of service and cannot route payments.

The *time-dilation attacks* described in [18] aim to eclipsing LN nodes to delay the time at which they become aware of new blocks. They target layer-2 mechanisms that rely on timely reactions, such as LN justice transactions. To make detection difficult they exploit the random arrival of new Bitcoin blocks (it is a Poisson process). Some countermeasures are proposed, such as watchtowers, which do not prevent the attack but raise its difficulty, especially if watchtowers are operated by third-party providers. They mention that this attack can be also amplified if the attacker performs a DoS attack against Bitcoin: this brings us to the conclusion that time-dilation attacks, and in general eclipse attacks, can be used to amplify the mass double-spend attack since they can further reduce the time honest nodes have to react to the attack.

Finally, mass exit attacks on Plasma are studied in [6].

#### 8 CONCLUSIONS

In this paper we have analyzed two attacks that exploit congestion on the bitcoin blockchain to cause damage on the Lightning Network. Using historical mempool data taken during periods of high and low congestion, we have simulated two attacks: in the case of the zombie attack, funds remain locked for a lot of blocks before users are able to retrieve them, while, in the mass double-spend attack, funds are at risk of being stolen.

We presented a theoretical justification for the effectiveness of the attacks, even when the adversary controls only a very small coalition. This is based on the observation that the LN network is scale-free, and scale-free graphs have large k-lopsided cuts, for small values of k. This suggests that our attacks should become more effective for larger network sizes, for the same coalition size, k. In particular, the average expected profit of a node participating in the worst-possible k-coalition should grow in the future with network size.

Our simulation results suggest that watchtower algorithms should be configured carefully. Ideally, they should monitor layer-1 congestion, and respond aggressively in the case of high congestion.

We leave as future work the study of both attacks under a more detailed model that incorporates transaction fees in the costs of the participants.

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# A LIGHTNING NETWORK CHANNELS MECHANISMS

The Lightning Network introduces the concept of *channels*, that can be opened between two parties, in order to execute off-chain

transfers of funds. Whenever at least one of the channel participants wants to claim their balance on layer-1, the channel must be closed, either cooperatively (if both parties agree), or unilaterally, by posting the last state of the channel's balance sheet.

To ensure the security of users' funds, the Lightning Network relies on the assumption that the layer-1 will always be able to process legitimate users' transaction in a reasonable amount of time, in order to close unusable channels and dispute fraudulent behavior from dishonest actors. If the state which is posted on-chain does not correspond to the most recent state of the balance sheet, honest users have a certain time window (agreed on channel opening) to prove that the posted commitment is not the most recent one, by broadcasting the so-called *justice* (or *penalty*) transaction. The amount of time (in blocks) that users have to prevent the loss of funds is agreed on channel opening by both parties, as described in the BOLT (Basis of Lightning Technology) specifications [4], which describe the exchange of messages between two LN nodes that want to establish a payment channel. In particular, when a new channel is created between two parties, Alice and Bob, the parameters of the newly created channels are agreed. To do this, an open\_channel message is sent from Alice to Bob: a number of parameters regarding the channel are agreed; among them, we are mostly interested in the to\_self\_delay parameter. This parameter indicates the number of blocks that the other party (i.e., Bob) has to wait in case he tries to unilateral close the channel. Later, an accept\_channel message is sent from Bob to Alice as a reply, indicating the desired value to be assumed for the to\_self\_delay parameter of Alice.