# Strategic Analysis to defend against Griefing Attack in Lightning Network

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**Abstract**

Payments routed in Lightning Network are susceptible to a *griefing attack*. In this attack, the channels get blocked, and the affected parties cannot process any payment request. Our work is the first to analyze griefing attacks in Hashed Timelock Contract or *HTLC*, from a game-theoretic point of view. Using the same model, we analyze another payment protocol Hashed Timelock Contract with Griefing-Penalty or *HTLC-GP*, which was proposed to counter griefing attacks. We find that *HTLC-GP* is *weakly effective* in disincentivizing the attacker. To further increase the cost of attack, we introduce the concept of *guaranteed minimum compensation* and integrate it into *HTLC-GP*. This modified payment protocol is termed HTLC-GP$^\zeta$ and unlike *HTLC-GP*, the protocol considers the participants to act rationally. By experimenting on several instances of Lightning Network, we show that the capacity locked drops to 40% in the case of *HTLC-GP* when the rate of griefing-penalty is set to $4.5 \times 10^{-5}$, and 28% in the case of HTLC-GP$^\zeta$ when guaranteed minimum compensation is 2.5% of the transaction amount. These results justify our claim that HTLC-GP$^\zeta$ is better than *HTLC-GP* to counter griefing attacks.

*Keywords:* Lightning Network, Hashed Timelock Contract or *HTLC*, Griefing Attack, Dynamic Games of Incomplete Information, Griefing Penalty, Guaranteed Minimum Compensation.

## 1. Introduction

Blockchain has redefined trust in the banking system and business space. Transactions are settled without relying on any central authority [1]. Another benefit is that all the records in Blockchain are tamper-proof. Any party with bounded computation power cannot double-spend or delete a transaction. However, transaction throughput is quite low compared to conventional payment systems like Visa, PayPal [2] etc. It is due to computation overhead and expensive consensus mechanism [3], [4] which serves as a bottleneck while deployment.

Layer 2 protocols [5], [6] have gained prominence in recent years. Transactions can be settled faster without involving blockchain, except in the case of dispute resolution. Several solutions like payment channel [7], state channels [8], side-chain [9], commit-chains [10], and rollups [11] have been explored. These solutions are modular and can be changed as per user requirements, preventing any hard fork in the existing system. Payment Channels [12] are widely deployed for scalability. Except for recording the opening and closing of the payment channel in blockchain, the rest of the transactions are executed off-chain. Any two parties willing to transact but not directly connected by a payment channel can leverage the set of existing payment channels for the transfer of funds. Several interconnected payment channels form a Payment Channel

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Network or PCN. In practice, Lightning Network for Bitcoin [7] and Raiden Network for Ethereum [13] are the widely deployed PCNs. In the next section, we discuss the routing of payments in the Lightning Network.

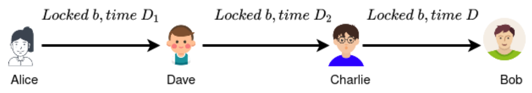

Figure 1: Formation of contract, forwarding conditional payment from *Alice* to *Bob*

*Payment in Lightning Network*

A payer can securely transfer funds to an intended recipient in Lightning Network using the protocol Hashed Timelock Contract or *HTLC*. We discuss *HTLC* with an example given in Fig.1. *Alice* intends to transfer $b$ coins to *Bob* via channels *Alice-Dave, Dave-Charlie*, and *Charlie-Bob*. *Bob* generates a condition and shares it with *Alice*. The latter uses it to forward a conditional payment to *Dave*, locking $b$ coins for time $D_1$. *Dave* forwards the payment to *Charlie*, locking $b$ coins for $D_2$ units of time. Finally, *Charlie* locks $b$ coins with *Bob* for time $D$, where $D_1 > D_2 > D$. To claim $b$ coins from *Charlie*, *Bob* must fulfill the condition within the time $D$. Once *Bob* has resolved the payment, the rest of the intermediaries can claim the coins as well. However, *HTLC* is susceptible to different attacks. We discuss one such attack, termed *griefing*, in the next section.

*Griefing Attack in Lightning Network*

In the payment instance provided in Fig.1, if *Bob* does not respond, then *Charlie* cannot settle the payment before $D$ units elapse. After the timeout period, *Charlie* goes on-chain to claim the refund, closes the channel *Charlie-Bob*, and unlocks the coins. However, *Bob* manages to lock $b$ coins in each of the preceding payment channels for time $D$ units [14]. This attack is a *griefing attack*. $D$ could be of the order of *24 hours*. Hence, none of the parties can utilize the coins locked in their respective off-chain contracts for an entire day. A malicious node can temporarily claim the network's liquidity by mounting the attack. Honest parties cannot earn a fee by processing transactions. In the next section, we discuss another payment protocol, Hashed Timelock Contract with Griefing-Penalty or *HTLC-GP* [15], that claims to counter griefing attacks.

*Overview of HTLC-GP and challenges faced*

Punishing a malicious node by using reverse bonds in an off-chain contract forwarding payments [16] or *griefing-penalty* in *HTLC-GP* [15], [17] to compensate honest parties has already been proposed. We provide a high-level overview of *HTLC-GP* using the payment instance stated in Fig.1. *Dave* now locks $l_1$ coins as a guarantee of compensation against $b$ coins locked by *Alice*, for time $D_1$. The terms of the contract are now redefined as: *If* Dave *responds within $D_1$, he claims $b$ coins and unlocks $l_1$ coins. If he fails to respond,* Alice *unlocks $b$ coins and claims $l_1$ coins as compensation.* Similarly, *Charlie* locks $l_1 + l_2$ coins for time $D_2$ as a guarantee of compensation against $b$ coins locked by *Dave* and *Alice*. If *Charlie* griefs, then the coins will be used for compensating *Alice* and *Dave*. *Bob* locks $l_1 + l_2 + l_3$ coins for time $D$ as a guarantee of compensation against $b$ coins locked by *Charlie*, *Dave*, and *Alice*. The procedure is illustrated in Fig.2(a).

*HTLC-GP* is effective under the assumption that the attacker will not respond at all. In that case, the victim settles the transaction in Blockchain, claims the compensation, and closes the channel. However, *Bob* can easily attack without paying a penalty. The terms of the contract state that *Dave* can claim compensation after $D$ units of time elapses. *Bob* realizes he can still mount the attack by resolving the payment just before the lock time of the off-chain contract elapse. There is no way for *Charlie* to figure out whether the delay was intentional or an artifact of network congestion. The former assumes *Bob* to be an honest party and co-operates with the latter to settle the payment mutually. Fig.2(b) shows how the malicious node successfully jams the network without paying any penalty. However, *Bob* ends up locking $l_1 + l_2 + l_3$ coins for $D$ units of time, just like the other affected parties.

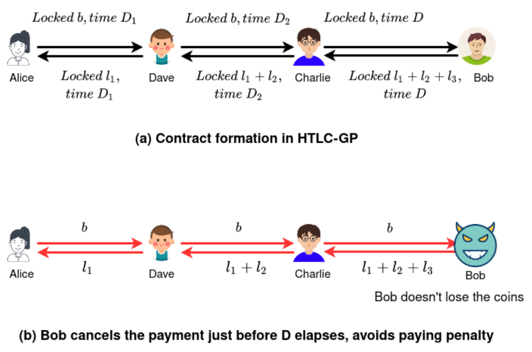
Locked $b$, time $D_1$
Locked $b$, time $D_2$
Locked $b$, time $D$
Alice
Dave
Charlie
Bob
Locked $l_1$, time $D_1$
Locked $l_1 + l_2$, time $D_2$
Locked $l_1 + l_2 + l_3$, time $D$
(a) Contract formation in HTLC-GP
$b$
$b$
$b$
Alice
Dave
Charlie
Bob
$l_1$
$l_1 + l_2$
$l_1 + l_2 + l_3$
Bob doesn't lose the coins
(b) Bob cancels the payment just before D elapses, avoids paying penalty

Figure 2: Griefing attack in HTLC-GP

We realize that security analysis of *HTLC-GP* fails to establish its credibility as a potential countermeasure. The underlying cryptographic construction of the protocol relies on a punishment mechanism that must be argued from a game-theoretic point of view. Further, *HTLC-GP* works under the classical assumption that an honest party is always altruistic. On the contrary, a rational participant will follow the steps mentioned in a protocol only if a deviation is not profitable. Existing analysis does not capture whether locking extra coins for such a long duration would affect a party's expected revenue.

## *1.1. Contributions*

We have made the following contributions:

- This is the first attempt to model griefing attack in *HTLC*, as a *dynamic game of incomplete information* between two players - one forwarding the payment and the other being the recipient. The latter party can either be uncorrupted, or it can be corrupted.
- Using the same model, we analyze another payment protocol, Hashed Timelock Contract with Griefing Penalty or *HTLC-GP* [15], that claims to counter griefing attack. Analyzing the game model for *HTLC-GP*, we find that the attacker has the option of griefing without paying any penalty. We realize that the protocol fails to compensate uncorrupted parties, and the security proof stated in [15] is not sufficient to justify the benefit of the countermeasure.
- We justify the effectiveness of *HTLC-GP* from the attacker's point of view. The metric *capacity locked* is used to measure the success rate of the attack. We observe that the capacity locked decreases in *HTLC-GP* compared to *HTLC* for a given incentive per attack. However, the loss in capacity locked is dependent on the rate of griefing-penalty. If the penalty locked for a given payment is too low, then the loss is negligible. Thus, we infer that *HTLC-GP* is *weakly effective* in disincentivizing the attack.
- We introduce the concept of *guaranteed minimum compensation*, denoted as $\zeta$, and integrate it into *HTLC-GP*. The modified protocol is termed HTLC-GP$^\zeta$ and the participants are considered to be rational. The cost of the attack can be increased substantially by increasing $\zeta$.
- Upon experimental analysis on several instances of Lightning Network, we show that if the guaranteed minimum compensation for each affected party is set to 2.5% of the transaction amount, the rate of griefing-penalty is $4.5 \times 10^{-5}$, and path length is set to 10, the capacity locked drops to 28%. The capacity locked is 27% less than the capacity locked in *HTLC-GP*. The results shows that HTLC-GP$^\zeta$ is far more effective than *HTLC-GP*. The code is provided in GitHub[1].

[1]`https://github.com/subhramazumdar/Strategic_Analysis_Griefing`

### 1.2. *Organization*

The rest of the paper is organized in the following way: Section 2 discusses the background and Section 3 discusses the state-of-the-art needed for understanding our paper. In Section 4, we provide a game-theoretical analysis of the payment protocol *HTLC*, and discuss griefing attack in this model. We have discussed an existing protocol, *HTLC-GP* that claims to counter griefing attack in Section 5. In Section 6, we have discussed a game model for *HTLC-GP* and analyzed the effectiveness of the protocol. In Section 7, we discuss the concept of *guaranteed minimum compensation* $\zeta$, and derive an expression for the maximum path length dependent on $\zeta$. We modify *HTLC-GP* into HTLC-GP$^\zeta$ by incorporating the concept of minimum compensation in Section 8. Experimental results obtained upon simulating the game models of *HTLC* and *HTLC-GP*, and measuring the efficiency of *HTLC-GP* and HTLC-GP$^\zeta$ is provided in Section 9. We conclude the paper in Section 10.

| Notation | Description |
|---|---|
| $G := (V, E)$ | A bidirected graph representing the Lightning Network |
| $V$ | Set of nodes in Lightning Network |
| $E$ | Set of payment channels in Lightning Network, $E \subset V \times V$ |
| $n$ | Length of the path $P$, also maximum allowed path length in Lightning Network |
| $U_0$ | Payer/Sender, $U_0 \in V$ |
| $U_n$ | Payee/Receiver, $U_n \in V$ |
| $\alpha$ | Amount to be transferred from $U_0$ to $U_n$ |
| $P$ | Path connecting $U_0$ to $U_n$ |
| $U_i \in V, i \in [0, n]$ | Nodes in $P, (U_i, U_{i+1}) \in E$ |
| $id_{i,j}$ | Identifier of channel $(U_i, U_j)$ |
| $locked(U_i, U_j)$ | Amount of funds locked by $U_i$ in the payment channel $(U_i, U_j)$ |
| $remain(U_i, U_j)$ | Net balance of $U_i$ that can be transferred to $U_j$ via off-chain transaction |
| $f(\alpha)$ | Processing fee charged for forwarding $\alpha$ coins |
| $\lambda$ | Security Parameter |
| $\mathcal{H}\{0,1\}^* \rightarrow \{0,1\}^\lambda$ | Standard Cryptographic Hash function |
| $\Delta$ | Worst-case confirmation time when a transaction is settled on-chain |
| $D$ | HTLC Timeout period |
| $M$ | Average mining fee for closing a payment channel |
| $\theta$ | Belief of a player in a 2-party dynamic Bayesian game |
| $\Gamma_{HTLC}$ | Extensive form of a 2-party dynamic Bayesian game in *HTLC* |
| $\gamma$ | Rate of griefing penalty (per minute) |
| $T$ | Lifetime of a channel |
| $t_{i,j}$ | The time at which the channel between $U_i$ and $U_j$ was opened |
| $t_{contract\_initiate}$ | Timestamp at which off-chain contract got initiated |
| $\Gamma_{HTLC-GP}$ | Extensive form of a 2-party dynamic Bayesian game in *HTLC-GP* |
| $\zeta$ | Guaranteed Minimum Compensation |
| $\tilde{n}$ | Maximum path length in HTLC-GP$^\zeta$, $\tilde{n} \leq n$ |
| $k$ | Ratio of the cumulative penalty locked by payer and the payment value locked by payee |
| $\gamma^{\zeta,k}$ | Rate of griefing-penalty in HTLC-GP$^\zeta$ for a given $\zeta$ and $k$ |

Table 1: Notations used in the paper

## 2. Background

We discuss the related background needed to understand our paper. The terms payer means the sender node. Similarly, payee/recipient means the receiver node. A node in the network is termed a party. The notation used in the paper has been defined in Table 1.

## *2.1. Lightning Network*

Lightning Network is a *Layer 2* protocol that sits on top of blockchain-based cryptocurrency Bitcoin. When two parties in the network wish to open a channel, they lock their coins in a 2-of-2 multi-signature contract. They create a new commitment transaction to update the channel's state and exchange their signature. Having the signature of the counterparty on his or her copy of the transaction allows the party to broadcast the latest valid transaction and close the channel unilaterally. A transaction can be invalidated by using a revocation mechanism stated in [7]. The mechanism requires the parties to share the secret keys used for signing the revoked transaction. When a party raises a dispute and goes on-chain, a time window is imposed which prevents the former from spending his coins immediately. The time window is enforced by using relative time locks [18]. If the counterparty finds the dispute to be invalid, he or she uses the secret key of the revoked transaction to spend the entire fund locked in the channel within the given time window. As a result, the other party that had raised an invalid dispute loses funds.

## *2.2. Hashed Timelock Contract*

*Hashed Timelock Contract (HTLC)* [7] is a routing module used for payment across parties not directly connected by the payment channel. A payer $U_0$ wants to transfer funds to a payee $U_n$, using a network of channels across an $n$-hop route $\langle U_0, U_1, U_2, \ldots, U_n \rangle$. The payee $U_n$ creates a condition $Y$ defined by $Y = \mathcal{H}(s)$ where $s$ is a random string and $\mathcal{H}$ is a standard hash function. The payer shares the condition $Y$ with $U_0$. The latter uses the condition for conditional payment across the whole payment path. Between any pair of adjacent nodes $(U_i, U_{i+1})$, the hashed timelock contract is defined by $HTLC(U_i, U_{i+1}, Y, b, D)$. It implies that $U_i$ lock $b$ coins in the off-chain contract. The coins locked can be claimed by the party $U_{i+1}$ only if it releases the correct preimage $s' : Y = \mathcal{H}(s')$ within time $D$. If $\mathcal{H}$ is a collision-resistant hash function, then $s' \neq s$ with negligible probability. If $U_{i+1}$ doesn't release the preimage within $D$, then $U_i$ settles the dispute on-chain by broadcasting the transaction. The channel between $U_i$ and $U_{i+1}$ is closed and $U_i$ unlocks the coins from the contract. If $U_{i+1}$ releases the preimage then it can either broadcast the transaction on-chain or settle the contract off-chain. Upon off-chain settlement, the contract is invalidated by creating a new commitment transaction, with $b$ coins being added to $U_{i+1}$'s balance.

## *2.3. Dynamic Games of Incomplete Information or Dynamic Bayesian Games*

In this class of games, players move in sequence, with at least one player being uncertain about another player's payoff. To approach these games, it is necessary to define a belief system and a player's behavioral strategy. We define a *type space* for a player that is the set of all possible types of that player. A *belief system* in a dynamic game describes the uncertainty of that player of the types of the other players. A *behavioral strategy* of a player $i$ is a function that assigns to each of $i's$ information set a probability distribution over the set of actions to the player $i$ at that information set, with the property that each probability distribution is independent of every other distribution. A dynamic game of incomplete information consists of [19]:

- A set of players $\mathcal{I}$;
- A sequence of histories $H^m$ at the $m^{th}$ stage of the game, each history assigned to one of the players (or to Nature/Chance);
- An information partition. The partition determines which of histories assigned to a player are in the same information set;
- A set of pure strategies for each player $i$, denoted as $S_i$;
- A set of types for each player $i : \theta_i \in \Theta_i$;
- A payoff function for each player $i : u_i(s_1, s_2, \ldots, s_l, \theta_1, \theta_2, \ldots, \theta_l)$;
- A joint probability distribution $p(\theta_1, \theta_2, \ldots, \theta_l)$ over types.

To analyze dynamic games with incomplete information, a new equilibrium concept *perfect Bayesian equilibrium* is used, which is defined as follows: *Perfect Bayesian Equilibrium*: A perfect Bayesian equilibrium in a dynamic game of incomplete information is a strategy profile $s$ and belief system $\theta$ such that:

- $s$ is *sequentially rational* given beliefs $\theta$. It means, given the beliefs and other players' strategies, no player can improve his or her payoffs at any stage of the game.
- $\theta$ is consistent with $s$, i.e., at information sets both on and off the equilibrium path, beliefs are determined by *Bayes' rule* and player's strategy profile $s$.

## 3. Related Works

A griefing attack is mounted to disrupt the network. The attack was first mentioned in [20]. In [21], the authors have applied griefing attack along with channel exhaustion for eliminating specific edges and paths in PCN. In [22], [23], an attacking strategy has been mentioned that revolves around overloading each channel with maximum unresolved *HTLC*s for multiple days.

*Impact of Griefing Attack.* Quite a lot of papers have studied the disastrous impact of griefing attack on PCN. Balance lockdown attack in Lightning Network has been described in [24]. A follow-up on this line of work, termed as *bank run attacks* on Bitcoin's Lightning Network, was empirically analyzed in [25]. The adversary generates several Sybil nodes that establish channels with existing nodes in the PCN. Experimental results show that griefing attack reduces the credibility of Lightning Network. Nodes start exiting the network and search for better alternatives. In [26], a *general congestion attack* was introduced, which generalizes the existing congestion attack in terms of attacking strategies and targeted metrics. The strategies discussed for mounting the attack focus on the network's liquidity.

*Existing Countermeasures.* Several countermeasures have been proposed to counter this attack. Apart from penalizing an attacker responsible for mounting the attack, using upfront payments for incentivizing rational nodes for faster resolution of payments has been discussed in [27]. However, this scheme introduces a huge amount of economic barrier for a payer. Also, it will never demotivate an attacker from mounting the attack as it will never lose any coins. Proof-of-Closure of channels was proposed in [28] where two timeouts were set for ab *HTLC*, a hard timeout, and a soft timeout period. The countermeasure is not at all effective. A malicious node does not lose anything, but an honest player loses its channel.

*Strategic Analysis of Payments.* Few existing works analyze the payments executed in Lightning Network from a game-theoretic point of view. In [29], a framework for formally characterizing the robustness of blockchain systems in the presence of Byzantine participants has been proposed. The paper defines the routing module *HTLC* as a game between three participants. However, they have considered that a payment can be accepted or rejected. This work doesn't capture the case when a malicious party can intentionally stop responding. It is not justified to consider a lack of response equivalents to rejecting a payment instantly since the parties cannot utilize the coins locked in the contract. Assigning a payoff of 0 for a failed payment doesn't account for the loss incurred due to the non-utilization of coins. Another work [30] discusses the shortcoming of the game model of multi-hop payment proposed in [29]. They have improved the model that is capable to cover *wormhole attacks* in the network. In [31], a game-theoretic analysis of atomic cross-chain swaps using *HTLC* has been provided. They have studied the impact of token price volatility on the strategic behavior of the participants initiating the swap and suggested the use of collateral deposits to prevent parties from canceling the swap. Using premium for fairness in the atomic cross-chain swap was proposed in [32]. The authors have suggested penalty as a countermeasure for countering the griefing attack. However, it fails to address the situation where the party can initiate the swap just before the elapsed lock time, evading penalty but still managing to lock the counterparty's coins.

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## 4. Griefing Attack and its Strategic Analysis

Before modeling griefing attack as a two-player *dynamic game of incomplete information* [19], we state the system requirements, attack model, and assumptions.

### *4.1. System Model*

Lightning Network is modeled as a bidirected graph $G := (V, E)$, where $V$ is the set of accounts dealing with cryptocurrency and $E$ is the set of payment channels opened between a pair of accounts. Every node charges a processing fee for relaying funds across the network. Fee is defined by function $f()$, where $f : \mathbb{R}^+ \rightarrow \mathbb{R}^+$. Correctness of payment across each channel is enforced cryptographically using hash-locks and time-locks [7]. Each payment channel $(U_i, U_j \in E$ is assigned an identifier $id_{i,j}$. The channel $id_{i,j}$ has an associated capacity $locked(U_i, U_j)$, denoting the amount locked by $U_i$ and $locked(U_j, U_i)$ denoting the amount locked by $U_j$. Let us denote the amount as $val_{i,j} = locked(U_j, U_i) + locked(U_i, U_j)$. The transaction recorded in the blockchain is $(id_{i,j}, val_{i,j}, t_{i,j}, T)$ where $t_{i,j}$ is the timestamp at which the channel was opened. In the context of the Bitcoin blockchain, this will be the block height. $T$ is the expiration time of the channel $id_{i,j}$, i.e., once a channel is opened, it is expected to remain active till $T$[2]. $remain(U_i, U_j)$ signifies the residual amount of coins $U_i$ can transfer to $U_j$ via off-chain transactions. $M$ denotes the average fee for mining a Bitcoin transaction.

Given an instance of payment where sender node $U_0$ wants to transfer $\alpha$ coins to node $U_n$ through path $P = \langle U_0 \rightarrow U_1 \rightarrow U_2 \ldots \rightarrow U_n \rangle$, each node $U_i$ charging a processing fee $f(\alpha)$. If $remain(U_i, U_{i+1}) \geq \alpha_i : \alpha_i = \alpha - \Sigma_{k=i}^{n} f(\alpha), i \in [0, n-1]$, then funds can be relayed across the channel $(U_i, U_{i+1})$. The residual capacity is updated as follows : $remain(U_i, U_{i+1}) = remain(U_i, U_{i+1}) - \alpha_i$ and $remain(U_{i+1}, U_i) = remain(U_{i+1}, U_i) + \alpha_i$. Any node $U_i$ forwards an amount $\alpha + (n-1-i)f(\alpha)$ to $U_{i+1}$. $U_n$ generates a payment condition $H = \mathcal{H}(x)$ and shares it with $U_0$. The *HTLC* timeout period in the contract between $U_i$ and $U_{i+1}$ is set to $D + (n-1-i)\Delta, i \in [0, n-1]$, $\Delta$ being the worst-case time taken to settle a transaction on-chain.

#### *4.1.1. System Assumption*

All the nodes in the network are rational [34], [35][3]. Rational processes always seek to maximize their expected utility. They will deviate from a prescribed protocol if and only if doing so increases their expected utility. Uncorrupted nodes act as honest nodes, following the protocol. The corrupt nodes receive a bribe for mounting the attack on other participants. Here even the adversary is rational and it will choose to attack only if their utility does not decrease in the process of attack. We assume that a channel between $U_i$ and $U_{i+1}$ is unilaterally funded by $U_i, i \in [0, n-1]$, i.e., $locked(U_{i+1}, U_i) = 0$. The maximum length for routing a payment is denoted by $n$.

*Functions used.* We define a function $O : \mathbb{R}^+ \times \mathbb{W} \times \mathbb{R}^+ \rightarrow \mathbb{R}^+ \cup \{0\}$, where $O(r_U, t, val)$ is the expected revenue a node $U$ would have earned had it utilized the amount $val$ for processing transactions in period of $t$ units given that $r_U$ is the rate of payments processed by $U$ per unit time. In other words, $O$ defines the *opportunity cost.* In our model, nodes are subjected to an opportunity cost of the coins they lock inside payment channels as well as in the off-chain time-locked contracts [36]. The primary source of revenue for a routing node in the Lightning Network is the fee obtained by processing transactions [37]. Also, the arrival of payment in a channel follows a Poisson process [38], [39]. $U$ expects each transaction size to be $per\_tx\_val$. Given the number of coins locked is $val$, the number of transactions $U$ expects to receive in period of $t$ units is $J = \frac{val}{per\_tx\_val}$. Given $X$ is the number of transactions in that interval or $X \sim Poisson(r_U t)$, we have.

$$P(X = x) = \frac{e^{-r_U t}(r_U t)^x}{x!} \tag{1}$$

where $0 \leq x \leq J$. Expected number of transactions in $t$ unit of time

$$E(X) = \sum_{x=0}^{J} x P(X = x) \tag{2}$$

[2]Each channel in Lightning Network have an infinite lifetime. However, we assume an upper bound on the channel lifetime for our analysis. Setting channel expiration time has been used in the literature as well [33]

[3]For our model, we restrict it to just rational participants. Since the attacker has a fixed budget, it will not be able to bribe all the nodes in the network. However, the Lightning network may have Byzantine as well as altruistic nodes. We leave the analysis of griefing attack in BAR model as future work.

The fee earned by processing a transaction of size $per\_tx\_val$ is defined as [40],[41]:

$$Fee_{per\_tx\_val} = base\_fee + fee\_rate \times per\_tx\_val \tag{3}$$

Thus, the revenue $U$ expects to earn within period $t$ or in other words, the opportunity cost $O(r_U, t, val)$ is

$$O(r_U, t, val) = E(X) Fee_{per\_tx\_val} \tag{4}$$

### *4.2. Attacker Model & Assumptions*

An attacker with budget $\mathcal{B}_{EX}$ has the objective of disrupting the network by jamming the network [34][4]. Given the budget, the attacker will be able to incentivize a certain number of nodes in the network to mount the griefing attack. We define the model and assumptions as follows:

- If a node has accepted the offer from the attacker, it will be considered corrupted. Such nodes act as per the instructions received from the attacker and lock as many coins as possible in the network.
- If a node is corrupt, it implies that the bribe offered is sufficient to cover the opportunity cost of locked coins.
- All corrupted nodes know each other and the rest of the uncorrupted nodes in the network. Uncorrupted nodes remain unaware of a given node's nature.
- Corrupted nodes may open additional payment channels in the network just for the attack.

#### *4.2.1. Methods for mounting Griefing Attack*

*Bribe offered per attack.* In the system model, we consider that each payment is of value $\alpha$. The attacker fixes the bribe offered to a node to $L$ coins. The amount $L$ is $\alpha + I_{D,\alpha} + C$, where $C$ is the cost of routing payment and $I_{D,\alpha}$ is used to compensate the node for keeping $\alpha$ coins non-utilized for the next $D$ units of time. $I_{D,\alpha} \approx 2O(r_U, D, \alpha), \forall U \in V$ so that once the corrupted node locks an amount $\alpha$ for time $D$, even after losing $O(r_U, D, \alpha)$, the net gain would still be at least $O(r_U, D, \alpha)$. This ensures that the corrupted nodes will not switch to being altruistic.

If node $U_n$ is corrupted, it executes a self-payment of amount $\alpha$ (where it acts as both payer and payee) via a route of the maximum allowed path length. The corrupted node can select either of the strategies for mounting the attack:

- Reject the payment just before lock time elapses: The corrupted node rejects the conditional payment forwarded by $U_{n-1}$ just before the contract's lock time elapses. There is a high chance that $U_{n-1}$ will choose to co-operate and settle the transaction off-chain. The benefit is that $U_n$ can go on executing several instances of griefing attacks without the need of opening a fresh channel each time.
- Do not respond: This is as per the conventional definition of griefing. $U_n$ chooses not to respond and $U_{n-1}$ closes the channel unilaterally after the contract's lock time expires.

We assume that the corrupted node selects the first method with probability $q$ and the second method with probability $1 - q, q \in [0, 1]$.

[4]In this work, we consider the incentives at play to be external to the system. It is standard practice, and several works have adhered to this model

## *4.3. Game Model*

We model the interaction between two entities present in path $P$: node $U_{n-1}$, which is supposed to forward the payment request, and $U_n$, the recipient of the payment. Assuming that every incidence of griefing attack gets reported in the network, $U_{n-1}$ form a belief, defined as $\theta$, where $\theta \in [0, 1]$. $U_n$ can be *corrupted* with probability $\theta$ or *uncorrupted* with probability $1 - \theta$.

*Belief Model*: Any uncorrupted player is unaware of the attacker's budget. Since an attacker wants to corrupt as many nodes as possible for a given budget, it will select nodes in the network that either has low centrality measure or a meager expectation of earning by processing transaction. If the node has a high degree of betweenness centrality, it is difficult to corrupt such a node as it would prefer to act honestly rather than accept the bribe. A rational player forms a belief about the expected behavior of other nodes based on their position in the network and their reputation.

*Choice of players*: The interaction can be modeled for any pair of node $U_i$ and $U_{i+1}, i \in [0, n-2]$. However, a malicious node executes a self-payment via maximum path length and griefs, as per the instruction of the attacker. Other intermediate nodes can grief as well, but the attacker may not be interested in bribing a node that will not maximize the damage for a given cost of the attack. Hence, griefing will not be the best strategy for a rational intermediate node routing the payment. We discuss the model for interaction between $U_{n-1}$ and the payee $U_n$, and define the actions of $U_{n-1}$ and $U_n$:

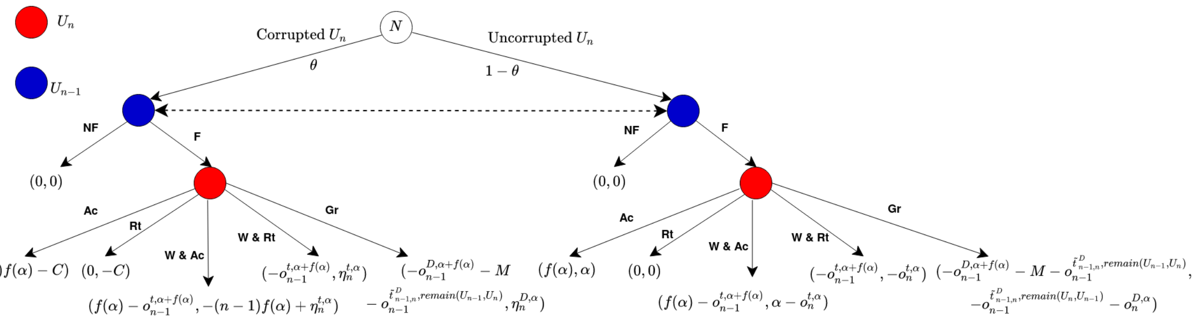
- *$U_{n-1}$'s action*: The action space of $U_{n-1}$ is defined as follows: it can either *forward (F)* the conditional payment to $U_n$ or it can choose to *not forward (NF)*. If it chooses to forward the payment, it forms a contract with $U_n$, locking the designated amount in the channel $id_{n-1,n}$ for time $D$, which is the HTLC timeout period. Simultaneously, $U_{n-2}$ has locked $\alpha + f(\alpha)$ in the contract established with $U_{n-1}$ in channel $id_{n-2,n-1}$. If $U_n$ claims $\alpha$ coins instantly, then $U_{n-1}$ can claim $\alpha + f(\alpha)$ coins from $U_{n-2}$, resulting in a profit of $f(\alpha)$. If the former delays, then $U_{n-1}$ starts incurring loss due to unavailability of liquidity in channel $id_{n-2,n-1}$. If $U_n$ doesn't respond within the deadline, then $U_{n-1}$ closes the channel and withdraws its coins from the contract.
- *$U_n$'s action*: If $U_{n-1}$ has forwarded the payment, then $U_n$ can choose its action from the following: *accept the payment* or *Ac*, *reject the payment* or *Rt*, *wait and then accept* or *W & Ac*, *wait and then reject* or *W & Rt*, and *grief* or *Gr*.
  - An *uncorrupted* $U_n$'s expected behavior is to resolve the payment instantly, i.e., *Ac* or *Rt*. Still, there is a probability that it ends up delaying or griefing. These actions lead to a loss in terms of the opportunity cost of locked coins and the closure of the channel.
  - A *corrupted $U_n$'s* expected behavior is to grief, *Gr* or wait and reject the payment, *W & Rt*, just before contract timeout. The attacker offers a bribe to such a node and instructs to mount the griefing attack.

We model interaction between $U_{n-1}$ and $U_n$ as a *dynamic Bayesian game* $\Gamma_{HTLC}$. The game begins with Nature (**N**) choosing the type of $U_n$, either *corrupted* or *uncorrupted*, respectively. $U_{n-1}$ believes that a corrupted $U_n$ will be selected with probability $\theta$, whereas an uncorrupted $U_n$ will be selected with probability $1-\theta$. After **N** makes its move, $U_{n-1}$ selects its strategy based on the belief of $U_n$'s type. Finally, $U_n$ chooses its strategy, provided $U_{n-1}$ has forwarded the payment.

**Definition 1.** *The extensive-form game $\Gamma_{HTLC}$, represented in Fig.3, is defined as tuple $\Gamma_{HTLC} = \langle N, (\Theta_{U_{n-1}}, \Theta_{U_n}), (S_{U_{n-1}}, S_{U_n}), p_{U_{n-1}}, (u_{U_{n-1}}, u_{U_n})\rangle$ [42]:*

- *The set of players $N = \{U_{n-1}, U_n\}$*
- *Player $U_i$ just has one type, i.e., rational. Thus $\Theta_{U_{n-1}} = \{rational(r)\}$. Since, it is a singleton set, we ignore this factor while defining payoff.*
- *The type of player $U_n$ defined as $\Theta_{U_n} = \{Corrupted(co),\ Uncorrupted\ (uco)\}$*
- *The set of actions for player $U_{n-1}$, $S_{U_{n-1}} = \{F, NF\}$*
- *The set of actions for player $U_n$, $S_{U_n} = \{Ac,\ Rt,\ W\ \&\ Ac,\ W\ \&\ Rt,\ Gr\}$*

- *Probability function $p_{U_i}$ is a function from $\Theta_{U_{n-1}}$ into $p(\Theta_{U_n})$, where the $p(\Theta_{U_n})$ denotes the set of probability distribution over $\Theta_{U_n}$. Since $U_{n-1}$ has just one type. $p_{U_{n-1}}$ specifies a probability distribution $p_{U_{n-1}}(|r)$ over the set $\Theta_{U_n}$ representing what player $U_{n-1}$ beliefs about the type of player $U_n$. Here $p_{U_{n-1}}(Corrupted) = \theta$, $p_{U_{n-1}}(Uncorrupted) = 1 - \theta$.*
- *The payoff function $u_k : \Theta \times S \to \mathbb{R}$ for any player $k \in \{U_{n-1}, U_n\}$, where $\Theta = \Theta_{U_n}$ and $S = S_{U_{n-1}} \times S_{U_n}$, is such that for any profile of actions and any profile of types $(\hat{\theta}, s) \in \Theta \times S$, specifies the payoff the player $k$ would get, if the player's actual type were all as in $\hat{\theta}$ and the players all chose their action as in $s$.*



$U_n$
$U_{n-1}$
$N$
Corrupted $U_n$
$\theta$
Uncorrupted $U_n$
$1-\theta$
NF
F
$(0,0)$
Ac
Rt
W & Ac
W & Rt
Gr
$(f(\alpha), -(n-1)f(\alpha) - C)$
$(0, -C)$
$(f(\alpha) - o_{n-1}^{t,\alpha+f(\alpha)}, -(n-1)f(\alpha) + \eta_n^{t,\alpha})$
$(-o_{n-1}^{t,\alpha+f(\alpha)}, \eta_n^{t,\alpha})$
$(-o_{n-1}^{D,\alpha+f(\alpha)} - M - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)}, \eta_n^{D,\alpha})$
NF
F
$(0,0)$
Ac
Rt
W & Ac
W & Rt
Gr
$(f(\alpha), \alpha)$
$(0,0)$
$(f(\alpha) - o_{n-1}^{t,\alpha+f(\alpha)}, \alpha - o_n^{t,\alpha})$
$(-o_{n-1}^{t,\alpha+f(\alpha)}, -o_n^{t,\alpha})$
$(-o_{n-1}^{D,\alpha+f(\alpha)} - M - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)}, -o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_n,U_{n-1})} - o_n^{D,\alpha})$

Figure 3: Extensive form of game $\Gamma_{HTLC}$

### *4.3.1. Payoff Model*

If $U_{n-1}$ chooses not to forward, then either party receives a payoff 0 since no off-chain contract got established, i.e., $u_{U_{n-1}}(\theta_b, NF, s_b) = u_{U_n}(\theta_b, NF, s_b) = 0, \theta_b \in \Theta_{U_n}$ and $s_b \in S_{U_n}$.

We analyze the payoff of $U_{n-1}$ when it has chosen $F$:

**A. N** had chosen an *uncorrupted* $U_n$. We analyze the payoff of each case:

I. Instantaneous Response, i.e., $t \to 0$: Payoff of both the parties, is discussed.

a. *$U_n$ accepts the payment*: $U_n$ claims the payment and $U_{n-1}$ gets processing fee $f(\alpha)$ from its preceding neighbour $U_{n-2}$. The payoffs are defined as $u_{U_{n-1}}(uco, F, Ac) = f(\alpha)$ and, $u_{U_n}(uco, F, Ac) = \alpha$ respectively.

b. *$U_n$ rejects the payment*: None of them gains anything, and the channel balance is restored. $u_{U_{n-1}}(uco, F, Rt) = u_{U_n}(uco, F, Rt) = 0$.

II. Delayed Response, i.e., $0 < t < D$: Payoff of both the parties is discussed.

a. *$U_n$ waits and then accepts the payment*:

- $U_{n-1}$ can earn $f(\alpha)$ only after $U_n$ resolves the payment. The delay of $t$ units of time in acquiring $\alpha + f(\alpha)$ coins from $U_{n-2}$ results in loss of profit defined by $O(r_{U_{n-1}}, t, \alpha + f(\alpha))$. This is the expected revenue $U_{n-1}$ could have earned by utilizing $\alpha + f(\alpha)$ within the next $t$ unit of time. It is also denoted as $o_{n-1}^{t,\alpha+f(\alpha)}$. This factor is subtracted from the payoff $U_{n-1}$ obtains if $U_n$ had accepted the payment instantly. $u_{U_{n-1}}(uco, F, W \ \& \ Ac) = f(\alpha) - o_{n-1}^{t,\alpha+f(\alpha)}$.
- $U_n$ waits and responds at any time $0 < t < D$. However, the more it delays, the more it loses the opportunity to earn profit by utilizing $\alpha$ coins. The expected profit that could have been made using $\alpha$ within the next $t$ units of time is $O(r_{U_n}, t, \alpha)$, also denoted as $o_n^{t,\alpha}$. As $U_n$ has delayed in acquiring $\alpha$ coins, it will lose this opportunity cost, proving that delaying is costly. Thus, $u_{U_n}(uco, F, W \ \& \ Ac) = \alpha - o_n^{t,\alpha}$.

b. *$U_n$ waits and then rejects the payment*: The payoff of $U_{n-1}$, denoted as $u_{U_{n-1}}(uco, F, W \ \& \ Rt)$, is $-o_{n-1}^{t,\alpha+f(\alpha)}$ . Payoff of $U_n$, denoted as $u_{U_n}(uco, F, W \ \& \ Rt)$, is $-o_n^{t,\alpha}$, since it doesn't claim any coins by canceling the payment.

III. $U_n$ *griefs*: If $U_n$ fails to respond within time $D$, $U_{n-1}$ will close the channel by going on-chain.

- $U_{n-1}$ cannot claim $\alpha + f(\alpha)$ coins from $U_{n-2}$. If $U_{n-1}$ could have acquired the coins, then it would have earned a revenue $O(r_{U_{n-1}}, D, \alpha + f(\alpha))$ by utilizing $\alpha$ coins within the next $D$ unit of time. This is the loss incurred, also denoted as $o_{n-1}^{D,\alpha+f(\alpha)}$. Additionally, due to closure of channel, $U_{n-1}$ fails to utilize the residual capacity $remain(U_{n-1}, U_n)$ for the next $T - (D + t_{contract\_initiate} - t_{n-1,n})$ unit of time, where $t_{n-1,n}$ is the timestamp at which channel $id_{n-1,n}$ was opened and $t_{contract\_initiate}$ is the current timestamp at which the off-chain contract got initiated in the channel. We use a shorter notation $\tilde{t}_{n-1,n}^{D}$ to denote $T - (D + t_{contract\_initiate} - t_{n-1,n})$. This is defined by $O(r_{U_{n-1}}, T - (D + t_{contract\_initiate} - t_{n-1,n}), remain(U_{n-1}, U_n))$ or $o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)}$. Along with that $U_{n-1}$ has to pay the transaction fee $M$ for settling on-chain. Hence, payoff $u_{U_{n-1}}(uco, F, Gr) = -o_{n-1}^{D,\alpha+f(\alpha)} - o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)} - M$.
- If $U_{n-1}$ had previously transferred coins to $U_n$ then $remain(U_n, U_{n-1}) > 0$. In that case, $U_n$ incurs a loss $O(r_{U_n}, T - (D + t_{contract\_initiate} - t_{n-1,n}), remain(U_n, U_n - 1))$, also denoted as $o_n^{\tilde{t}_{n-1,n}^{D}, remain(U_n,U_{n-1})}$, due to closure of channel after timeout period $D$. Additionally, it loses an opportunity cost of $O(r_{U_n}, D, \alpha)$, also denoted as $o_n^{D,\alpha}$, as it fails to earn and utilize the coins for other purpose. Hence, payoff $u_{U_n}(uco, F, Gr) = -o_n^{\tilde{t}_{n-1,n}^{D}, remain(U_n,U_{n-1})} - o_n^{D,\alpha}$. Since $U_n$ doesn't respond, we do not subtract $M$ from the payoff, as it has not gone on-chain for settling the transaction.

**B**. **N** has chosen a corrupted $U_n$. The latter executes a self-payment of amount $\alpha$ via a path of length $n$ via $n-1$ intermediaries. The amount forwarded is $\alpha + (n-1)f(\alpha)$, where, $f(\alpha)$ is the fee charged by an intermediate node. Since the cost incurred per payment is $C$ and $U_n$ has to keep $\alpha$ coins locked for time $D$, the bribe offered must compensate for all these costs. The amount of bribe offered by the attacker is $L$ where $L = \alpha + C + I_{D,\alpha}$, where $I_{D,\alpha} \approx 2o_n^{D,\alpha}$. We assume that prior to mounting griefing attack, $U_{n-1}$ had not transferred any payment to $U_n$, i.e., $remain(U_n, U_{n-1}) = 0$. We analyze each case as follows:

I. Instantaneous Response, i.e., $t \to 0$:

a. $U_n$ *accepts the payment*: $U_n$ ends up losing approximatey $(n-1)f(\alpha)$[5], as it needs to pay $(n-1)$ intermediaries. It had already incurred a cost $C$. $U_{n-1}$ has successfully forwarded the amount. Thus, payoffs are $u_{U_{n-1}}(co, F, Ac) = f(\alpha)$ and $u_{U_n}(co, F, Ac) = -C - (n-1)f(\alpha)$.

b. $U_n$ *rejects the payment*: $u_{U_{n-1}}(co, F, Rt) = 0$ and $u_{U_n}(co, F, Rt) = -C$.

II. Delayed Response, i.e., $0 < t < D$:

a. $U_n$ *waits and then accepts the payment*:

- Payoff of $U_{n-1}$ is same as the payoff it had obtained when $U_n$ is not corrupted and chooses to wait and accept the payment. Thus $u_{U_{n-1}}(co, F, W \ \& \ Ac) = f(\alpha) - o_{n-1}^{t,\alpha+f(\alpha)}$.
- $\eta_n^{t,\alpha}$ defines the net profit received by $U_n$ for keeping $\alpha$ coins unutilized till time $t$, where:

$$\eta_n^{t,\alpha} = \begin{cases} -C - O(r_{U_n}, t, \alpha), & 0 < t < D - \delta \\ L - C - O(r_{U_n}, t, \alpha), & t \geq D - \delta \end{cases} \tag{5}$$

Delaying till time $t < D - \delta$, will not result in any profit, $U_n$ loses the setup cost and the revenue had it utilized $\alpha$ for $t$ units of time. If it delays for at least $D - \delta$, it gets paid for the work done, i.e. $\eta_n^{D-\delta,\alpha}$. Since $\delta \to 0$, $\eta_n^{D-\delta,\alpha} \approx \eta_n^{D,\alpha} = L - C - O(r_{U_n}, D, \alpha)$. But $I_{D,\alpha} \approx 2o_n^{D,\alpha}$, which implies $L - C - o_n^{D,\alpha} = \alpha + C + I_{D,\alpha} - C - o_n^{D,\alpha} \approx \alpha + o_n^{D,\alpha}$. Upon accepting a self-payment, it ends up paying a processing fee $f(v)$ to $n-1$ intermediaries. Thus, the payoff of $U_n$, $u_{U_n}(co, F, W \ \& \ Ac) = -(n-1)f(\alpha) + \eta_n^{t,\alpha}$.

[5]The fee is charged on the amount being routed, if a node $U_i$ is routing $\alpha + (n-i-1)f(\alpha)$, then fee must be $f(\alpha + (n - 1 - i)f(\alpha))$. We assume that $\alpha + (n-1-i)f(\alpha) \approx \alpha$ since the fee $f(\alpha)$ is negligible compared to $\alpha$.

b. $U_n$ *waits and then rejects the payment*: Payoff of $U_{n-1}$ and $U_n$ are $u_{U_{n-1}}(co, F, W \text{ \& } Rt) = -o_{n-1}^{t,\alpha+f(\alpha)}$ and $u_{U_n}(co, F, W \text{ \& } Rt) = \eta_n^{t,\alpha}$ respectively.

III. $U_n$ *griefs*: $U_n$ successfully mounts the attack, it gets an incentive $L$ from attacker. It loses $C$, which is the cost for mounting the attack and the opportunity cost $o_n^{D,\alpha}$. Since the channel is unilaterally funded by $U_{n-1}$, $remain(U_n, U_{n-1}) = 0$. Thus there is no loss associated due to closure of channel. The payoff of $U_{n-1}$ is the same as the payoff it had obtained when $U_n$ is uncorrupted and chooses to grief. Thus, $u_{U_{n-1}}(co, F, Gr) = -o_{n-1}^{D,\alpha+f(\alpha)} - o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)} - M$ and $u_{U_n}(co, F, Gr) = L - C - o_n^{D,\alpha} = \eta_n^{D,\alpha}$.

### *4.4. Game Analysis*

Given $U'_{n-1}s$ belief that $\mathbf{N}$ selects a corrupted $U_n$ with probability $\theta$ and an uncorrupted $U_n$ with probability $1-\theta$, the expected payoff of $U_{n-1}$ is calculated by applying backward induction on the game tree $\Gamma_{HTLC}$ shown in Fig. 3. If $U_{n-1}$ plays *NF*, then $U_n$ cannot take any action, hence both gets a payoff of 0. If $U_{n-1}$ plays $F$; an *uncorrupted* $U_n$ chooses $Ac$ as its best response since $u_{U_n}(uco, F, Ac) \geq u_{U_n}(uco, F, s')$, $\forall s' \in S_{U_n}$; corrupted $U_n$ can choose either to *grief* or *Wait & Reject* at $D-\delta$ as its best response since $u_{U_n}(co, F, Gr) = u_{U_n}(co, W \text{ \& } Rt$ at time $D-\delta) \geq u_{U_n}(co, F, s''), \forall s'' \in S_{U_n}$. A corrupted $U_n$ applies mixed strategy, either choosing to *Grief* with probability $1-q$ or it can *Wait and Reject* at time $D-\delta$ with probability $q$. The expected payoff of $U_{n-1}$ for selecting *forward*, denoted as $\mathbb{E}_{U_{n-1}}(F)$, and expected payoff for selecting *not forward*, denoted as $\mathbb{E}_{U_{n-1}}(NF)$ are:

$$\begin{aligned} \mathbb{E}_{U_{n-1}}(F) = \theta\Big( - q o_{n-1}^{D-\delta,\alpha+f(\alpha)} + (1-q)(-o_{n-1}^{D,\alpha+f(\alpha)} - o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)} - M)\Big) \\ +(1-\theta) f(\alpha) \\ \mathbb{E}_{U_i}(NF) = 0 \end{aligned} \tag{6}$$

Since $\delta \rightarrow 0$, we consider $o_{n-1}^{D-\delta,\alpha+f(\alpha)} \approx o_{n-1}^{D,\alpha+f(\alpha)}$. Substituting in Eq. 6, $\mathbb{E}_{U_{n-1}}(F) > \mathbb{E}_{U_{n-1}}(NF)$, if $\theta < \frac{f(\alpha)}{o_{n-1}^{D,\alpha+f(\alpha)} + f(\alpha) + (1-q)(o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)} + M)}$. Hence, $U_{n-1}$ chooses *Forward* if $\theta < \frac{f(\alpha)}{o_{n-1}^{D,\alpha+f(\alpha)} + f(\alpha) + (1-q)(o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)} + M)}$, else it chooses *Not Forward*; *corrupted* $U_n$ can either choose *Grief* or *Wait & Reject* at time $D-\delta$; *uncorrupted* $U_n$ chooses *Accept*; is a perfect Bayesian equilibrium.

*Comparative Static Analysis.* We take the derivative of $\mathbb{E}_{U_{n-1}}(F)$ with respect to $\theta$, to observe how the expected payoff of $U_{n-1}$ changes with small change in $\theta$, keeping other variables constant.

$$\frac{\mathrm{d}\mathbb{E}_{U_{n-1}}(F)}{\mathrm{d}\theta} = -f(\alpha) - o_{n-1}^{D,\alpha+f(\alpha)} - (1-q)(o_{n-1}^{\tilde{t}_{n-1,n}^{D}, remain(U_{n-1},U_n)} + M) \tag{7}$$

$\frac{\mathrm{d}\mathbb{E}_{U_{n-1}}(F)}{\mathrm{d}\theta} < 0$ implies that $\mathbb{E}_{U_{n-1}}(F)$ is a decreasing function upon varying $\theta$. The higher the probability of selecting a corrupted, the expected payoff of $U_{n-1}$ will go down because of the probability of facing an attack increases. The loss incurred is mainly due to delay in resolution of payment and closure of channel (in some cases), as fee $f(\alpha)$ is negligible compared to the other two factors. In other words, if $\theta$ decreases, the higher the chance an *uncorrupted* recipient gets selected. $U'_{n-1}s$ expected payoff will increase.

In the next section, we will analyze another protocol, Hashed Timelock Contract with Griefing Penalty or *HTLC-GP*, that claims to disincentivize griefing attack.

## 5. Hashed Timelock Contract with Griefing Penalty or HTLC-GP

We discuss a payment protocol, proposed in one of our papers [15], [17] that uses penalty as a countermeasure. The protocol *HTLC* is modified to counter griefing attack, thus it is termed as Hashed Timelock Contract with Griefing Penalty or *HTLC-GP*. If the party griefs, it gets penalized, and the amount locked is distributed as compensation amongst the affected parties. The total penalty charged is proportional to the summation of the collateral locked in each channel, forming the path routing payment. *Collateral locked* in a channel by an off-chain contract is the product of coins locked in the off-chain contract and timeout period of the contract. This protocol forms the basis of defining the model for game-theoretic analysis and is later used for studying the effectiveness of penalty as a countermeasure.

## *5.1. Overview*

If the party wants to cancel the conditional payment in *HTLC*, it may simply request the counterparty forwarding the contract to cancel it mutually. The counterparty complies with the request, as it has no intention of keeping the coins unutilized. To incorporate penalty in *HTLC*, both parties must lock coins. The condition is that if a party that has formed the contract for claiming a conditional payment needs to resolve it within a given time. Failure to respond will result in the loss of coins. There is no way for a party to unilaterally cancel the conditional payment by going on-chain in *HTLC*. The counterparty may take advantage of this situation and refuse to cancel the contract mutually. After the lock time elapses, the counterparty goes on-chain and claims the penalty. This is termed as the problem of *reverse griefing*. Thus, a new protocol termed as *HTLC-GP* was proposed. It is a two-round protocol where the first round involves locking of penalty, termed as *Cancellation round*. The round starts from the payee and proceeds in the reverse direction. The penalty is locked by the party as a guarantee against a payment to be forwarded in the next round. The second round is termed as *Payment round*. It involves locking the payment value in off-chain contracts from payer to payee.

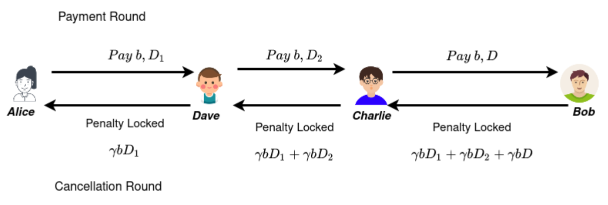


Figure 4: Formation of contract in *HTLC-CP*

A high-level overview of a routing protocol using penalty is explained with the help of an example shown in Fig. 4. *Alice* wants to transfer $b$ units to *Bob*. Each party that forwards a payment must be guaranteed by its counterparty to receive compensation if there is an incidence of griefing attack. The amount of compensation charged must be proportional to the collateral locked in the path. We define this proportionality constant as the *rate of griefing-penalty per unit time*, denoted as $\gamma$.

The first round termed as *Cancellation round* proceeds in the following way: *Bob* has to lock $\gamma b D_1 + \gamma b D_2 + \gamma b D$ coins for $D$ unit of time. This amount is the cumulative penalty to be distributed among *Alice, Dave* and *Charlie*, if Bob griefs. After *Charlie* receives the cancellation contract, he locks $\gamma b D_1 + \gamma b D_2$ in the contract formed with *Dave* for $D_2$ units. The latter locks $\gamma b D_1$ coins in the contract formed with *Alice* for $D_1$ units of time. The second round termed as *Payment round* proceeds in a similar way like in HTLC. Payment value $b$ is forwarded from *Alice* to *Bob* via the intermediaries.

### *Calculation of cumulative penalty*

In the example, *Bob* is required to lock $\gamma b D_1 + \gamma b D_2 + \gamma b D$ coins as a guarantee against the payment amount to be forwarded by *Charlie*. Since the lock time of the contract is $D$, one might question why *Bob* must take into account the lock time of the other contracts while locking penalty. We do so to prevent other intermediate parties from becoming a victim of reverse griefing. Consider the situation where *Bob* locks $3\gamma b D$ coins as penalty, *Charlie* locks $2\gamma b D_2$ as penalty and *Dave* locks $\gamma b D_1$. If *Bob* griefs, *Charlie* keeps the compensation $\gamma b D$ and forwards $2\gamma b D$ to *Dave*. *Dave* is greedy and refuses to mutually cancel the contract with *Charlie*. After elapse of $D_2$, it goes on-chain and claims $2\gamma D_2$. Since $D_2 > D$, *Charlie* incurs a loss of $2\gamma b(D_2 - D)$. Thus, we account for the lock time of each contract while calculating compensation to prevent the loss of coins of uncorrupted parties.

*Countering Griefing Attack*

Suppose *Bob* griefs. He will pay a compensation of $\gamma bD_1 + \gamma bD_2 + \gamma bD$ units to *Charlie*, as per the terms of the contract. After $D$ expires, *Charlie* goes on-chain. He closes the channel, unlocks $b$ coins, and claims compensation. He requests *Dave* to cancel the off-chain contract, offering a compensation of $\gamma bD_1 + \gamma bD_2$. *Dave* cancels the contract off-chain, unlocks $b$ units from the contract, and claims the compensation from *Charlie*. If *Charlie* decides to grief, *Dave* can claim the compensation by going on-chain and closing the channel. *Dave* requests *Alice* to cancel the contract by offering a compensation of $\gamma bD_1$. Except for *Bob*, none of the parties lose coins.

## 6. Strategic Analysis of HTLC-GP

### *6.1. System Model*

For payment of $\alpha$ from $U_0$ to $U_n$ via $(n-1)$ intermediaries, we denote the cumulative compensation offered to node $U_i$ by node $U_{i+1}$ upon forwarding an amount $\alpha_i = \alpha + (n-i-1)f(\alpha)$ as $Z_{\alpha_i,i+1}, i \in [0, n-1]$ where $Z_{\alpha_i,i+1} = Z_{\alpha_{i-1},i} + c_{\alpha_i,i}$, $c_{\alpha_i,i}$ is the compensation charged by node $U_i$ and $Z_{\alpha_{i-1},i}$ is used for compensating other nodes $U_j, j < i$. Note that $Z_{val,0} = 0, \forall val \in \mathbb{R}^+, \alpha_{n-1} = \alpha$. $c_{\alpha_i,i}$ charged by a node $U_i$, must be proportional to the collateral it has locked in the off-chain contract formed with node $U_{i+1}$ for timeout period $t_i, i \in [0, n-1]$. $t_i = t_{i+1} + \Delta$, $t_{n-1} = D$ and $c_{\alpha_i,i} = \gamma(\alpha + (n-i-1)f(\alpha))t_i$, $\gamma$ being the rate of griefing-penalty per unit time. An off-chain contract between node $U_i$ and $U_{i+1}$ requires $U_i$ locking an $\alpha_i$ coins and $U_{i+1}$ must lock $Z_{\alpha_i,i+1}$ coins. Here $Z_{\alpha_{n-1},n}$ denoted as $Z_\alpha = \sum\limits_{i=0}^{n-1} c_{\alpha_i,i}$ is locked by $U_n$ as guaranteed compensation against the amount locked by party $U_{n-1}$. Again, $U_{n-1}$ has locked $Z_{\alpha_{n-2},n-1}$ with the contract formed with $U_{n-2}$ for time $t_{n-1}$.

#### *6.1.1. Change in System Assumption*

In HTLC-GP, we consider a payment channel to be dual-funded. This implies that even in channel $id_{i,i+1}, i \in [0, n-1]$ both the parties $U_i$ and $U_{i+1}$ lock coins i.e., $locked(U_i, U_{i+1}) > 0$ and $locked(U_{i+1}, U_i) > 0$.

### *6.2. Redefining Attacker Model for HTLC-GP*

The cost of the attack increases as $U_n$ has to lock extra coins as guarantee. However, the attacker does not increase the incentive offered per attack. Thus, $U_n$ will not lock more than $\alpha$ coins. The former will distribute this amount between the cumulative penalty locked in the contract formed with $U_{n-1}$ and the amount to be forwarded for payment. This implies $\alpha$ is the summation of transaction value $v + (n-1)f(v)$ and the cumulative penalty imposed $Z_v = \sum\limits_{i=0}^{n-1} c_{v_i,i} = \gamma \sum\limits_{j=0}^{n-1} (v + (n-1-j)f(v))t_j$. Since $(n-1)f(v) << v$, we consider $v + Z_v = \alpha$ or, $v = \frac{\alpha}{1+\gamma \sum\limits_{j=0}^{n-1} t_j}$.

$U_n$ executes a self-payment of $v$ coins, choosing a path of length $n$. Each intermediate party and the recipient $U_n$ has to lock coins as a guarantee against the payment amount forwarded.

### *6.3. Game Model*

We model interaction between $U_{n-1}$ and $U_n$ as a *dynamic game of incomplete information* $\Gamma_{HTLC-GP}$. Fig. 5 illustrates the game tree. The game model is the same as the one used in $\Gamma_{HTLC}$, with the payoffs differing due to the introduction of penalty. Griefing is costly since the party responsible for griefing ends up losing coins. Nodes affected by the attack get compensated.

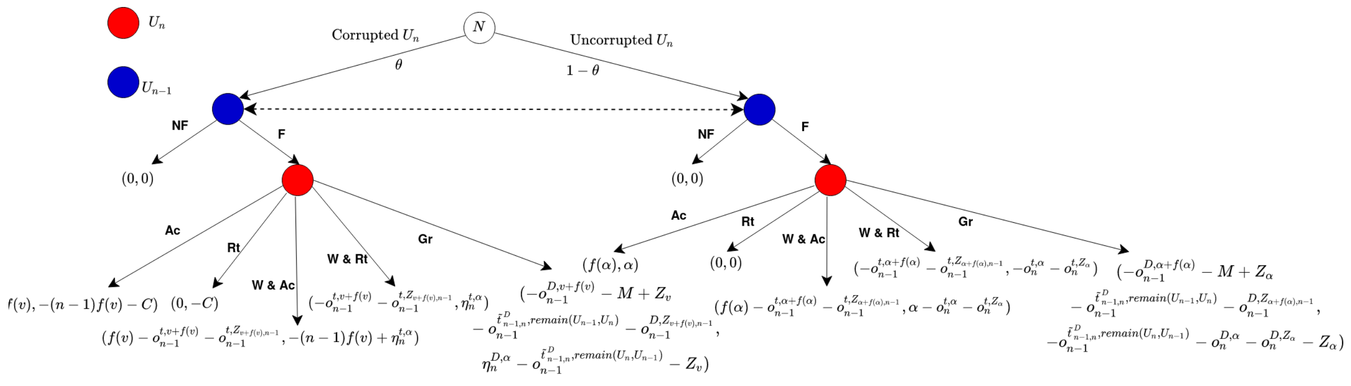

$U_n$
$U_{n-1}$
$N$
Corrupted $U_n$
$\theta$
Uncorrupted $U_n$
$1-\theta$
NF
F
$(0,0)$
Ac
Rt
W & Ac
W & Rt
Gr
$(f(v), -(n-1)f(v) - C)$
$(0, -C)$
$(f(v) - o_{n-1}^{t,v+f(v)} - o_{n-1}^{t,Z_{v+f(v),n-1}}, -(n-1)f(v) + \eta_n^{t,\alpha})$
$(-o_{n-1}^{t,v+f(v)} - o_{n-1}^{t,Z_{v+f(v),n-1}}, \eta_n^{t,\alpha})$
$(-o_{n-1}^{D,v+f(v)} - M + Z_v - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)} - o_{n-1}^{D,Z_{v+f(v),n-1}}, \eta_n^{D,\alpha} - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_n,U_{n-1})} - Z_v)$
NF
F
$(0,0)$
Ac
Rt
W & Ac
W & Rt
Gr
$(f(\alpha), \alpha)$
$(0,0)$
$(f(\alpha) - o_{n-1}^{t,\alpha+f(\alpha)} - o_{n-1}^{t,Z_{\alpha+f(\alpha),n-1}}, \alpha - o_n^{t,\alpha} - o_n^{t,Z_\alpha})$
$(-o_{n-1}^{t,\alpha+f(\alpha)} - o_{n-1}^{t,Z_{\alpha+f(\alpha),n-1}}, -o_n^{t,\alpha} - o_n^{t,Z_\alpha})$
$(-o_{n-1}^{D,\alpha+f(\alpha)} - M + Z_\alpha - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)} - o_{n-1}^{D,Z_{\alpha+f(\alpha),n-1}}, -o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_n,U_{n-1})} - o_n^{D,\alpha} - o_n^{D,Z_\alpha} - Z_\alpha)$

Figure 5: Extensive form of the game $\Gamma_{HTLC-GP}$

### *6.3.1. Payoff Model*

When $U_{n-1}$ chooses not to forward, both $U_{n-1}$ and $U_n$ receives a payoff 0 since no off-chain contract got established, i.e., $u_{U_{n-1}}(\theta_b, NF, s_b) = u_{U_n}(\theta_b, NF, s_b) = 0, \theta_b \in \Theta_{U_n}$ and $s_b \in S_{U_n}$. We analyze the payoff of each case when $U_{n-1}$ chooses to forward:

**A. N** had chosen an *uncorrupted* $U_n$. We analyze the payoff of each case:

I. Instantaneous Response, i.e., $t \to 0$: Upon instant acceptance or rejection of payment, the payoffs are the same as that observed in $\Gamma_{HTLC}$.

II. Delayed Response, i.e., $0 < t < D$:

a. $U_n$ *waits and then accepts the payment*:

- $U_{n-1}$ incurs loss due to delay in acquiring $\alpha + f(\alpha)$ coins from $U_{n-2}$ for $0 < t < D$. It also locks $Z_{\alpha_{n-2},n-1}$ coins as penalty in the contract formed with $U_{n-2}$, $\alpha_{n-2} = \alpha + f(\alpha)$. Even this amount lies unutilized, and we must deduct the loss incurred, denoted as $o_{n-1}^{t,Z_{\alpha+f(\alpha),n-1}}$, from the payoff. $u_{U_{n-1}}(uco, F, W \ \& \ Ac) = f(\alpha) - o_{n-1}^{t,\alpha+f(\alpha)} - o_{n-1}^{t,Z_{\alpha+f(\alpha),n-1}}$.
- $U_n$ has to keep $Z_\alpha$ coins locked in the contract established in channel $id_{n-1,n}$. Thus, it faces loss not only due to delay in claiming $\alpha$ coins from $U_{n-1}$ but also due to non-utilization of $Z_\alpha$. The expected profit that could have been made using $\alpha$ and $Z_\alpha$ within the next $t$ unit of time is $O(r_{U_n}, t, \alpha)$, also denoted as $o_n^{t,\alpha}$, and $O(r_{U_n}, t, Z_\alpha)$, denoted as $o_n^{t,Z_\alpha}$. Thus, $u_{U_n}(uco, F, W \ \& \ Ac) = \alpha - o_n^{t,\alpha} - o_n^{t,Z_\alpha}$.

b. $U_n$ *waits and then rejects the payment*: The payoff of $U_{n-1}$ is $u_{U_{n-1}}(uco, F, W \ \& \ Rt) = -o_{n-1}^{t,\alpha+f(\alpha)} - o_{n-1}^{t,Z_{\alpha+f(\alpha),n-1}}$ and payoff of $U_n$ is $u_{U_n}(uco, F, W \ \& \ Rt) = -o_n^{t,\alpha} - o_n^{t,Z_\alpha}$.

III. $U_n$ *griefs*:

- Even in this case, due to closure of channel $U_{n-1}$ fails to utilize the residual capacity $remain(U_{n-1}, U_n)$ for the next $T - (D + t_{contract\_initiate} - t_{n-1,n})$ unit of time. $U_{n-1}$ incurs a loss of $o_{n-1}^{D,\alpha+f(\alpha)} + o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)} + M$ and additional loss due to locking $Z_{\alpha+f(\alpha),n-1}$ coins in the contract formed in channel $id_{n-2,n-1}$. However, it can claim a compensation of $Z_\alpha$ upon closing the channel. Payoff $u_{U_{n-1}}(uco, F, Gr) = -(o_{n-1}^{D,\alpha+f(\alpha)} + o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)} + M + o_{n-1}^{D,Z_{\alpha+f(\alpha),n-1}}) + Z_\alpha$.
- $U_n$ incurs loss of $Z_\alpha$ coins to compensate $U_{n-1}$. It fails to earn revenue due to non-utilization of $Z_\alpha$ coins in channel $id_{n-1,n}$ for period $D$. Since now both the parties have to lock coins while opening channel, loss of channel affects $U_n$ if $remain(U_n, U_{n-1}) > 0$. The additional loses suffered are due to inability to claim $\alpha$ coins and using it within $D$ unit of time and failure in utilizing the residual capacity $remain(U_n, U_{n-1})$ for the next $T - (D + t_{contract\_initiate} - t_{n-1,n})$ unit of time. Thus, payoff of $U_n$ is $u_{U_n}(uco, F, Gr) = -o_n^{\tilde{t}^D_{n-1,n},remain(U_n,U_{n-1})} - o_n^{D,\alpha} - o_n^{D,Z_\alpha} - Z_\alpha$.

**B**. **N** has chosen a corrupted $U_n$. The latter executes a self payment of amount $v$, as stated in Attacker Model in Section 6.2. The payoffs for each case has been defined as follows:

I. Instantaneous Response, i.e., $t \to 0$: Upon instant acceptance or rejection of payment, the payoffs are the same as that observed in $\Gamma_{HTLC}$.

II. Delayed Response, i.e., $0 < t < D$:

a. *$U_n$ waits and then accepts the payment*:

- Payoff of $U_{n-1}$ is $u_{U_{n-1}}(co, F, W \ \& \ Ac) = f(v) - o_{n-1}^{t,v+f(v)} - o_{n-1}^{t,Z_{v+f(v),n-1}}$, due to delay in claiming of $v + f(v)$ coins as $U_n$ delays in resolving payment. Coins $Z_{v+f(v),n-1}$ remains locked in the contract formed with $U_{n-2}$.
- $U_n$ keeps $v + Z_v \approx \alpha$ coins locked for mounting the attack and receives a bribe $L$. The value $\eta_n^{t,\alpha}$ is the same as defined in Eq.5. Upon accepting a self-payment of amount $v$, the corrupted node ends up paying a processing fee $f(v)$ to $n-1$ intermediaries. Thus, the payoff of $U_n$ is $u_{U_n}(co, F, W \ \& \ Ac) = -(n-1)f(v) + \eta_n^{t,\alpha}$.

b. *$U_n$ waits and then rejects the payment*: Payoff of $U_{n-1}$, $u_{U_{n-1}}(co, F, W \ \& \ Rt) = -o_{n-1}^{t,v+f(v)} - o_{n-1}^{t,Z_{v+f(v),n-1}}$ and $u_{U_n}(co, F, W \ \& \ Rt) = \eta_n^{t,\alpha}$. When $t \approx D - \delta$ where $\delta \to 0, \eta_n^{t,\alpha}$ attains the maximum value.

III. *$U_n$ griefs*: $U_n$ successfully mounts the attack, it gets an incentive $L$ from the attacker, but at the same time loses $Z_v$ in order to compensate the affected parties. $U_{n-1}$ loses channel and the expected revenue due to coins remaining locked but gets the compensation $Z_v$. Thus, the payoffs of $U_{n-1}$ and $U_n$ are $u_{U_{n-1}}(co, F, Gr) = -o_{n-1}^{D,v+f(v)} - o_{n-1}^{D,Z_{v+f(v),n-1}} - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_{n-1},U_n)} - M + Z_v$ and $u_{U_n}(co, F, Gr) = L - C - o_n^{D,\alpha} - Z_v - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_n,U_{n-1})} = \eta_n^{D,\alpha} - Z_v - o_{n-1}^{\tilde{t}^D_{n-1,n},remain(U_n,U_{n-1})}$ respectively.

*6.4. Game Analysis*

The expected payoff of $U_{n-1}$ is calculated by applying backward induction to the game tree $\Gamma_{HTLC-Penalty}$ shown in Fig. 5. If $U_{n-1}$ plays *NF*, then $U_n$ cannot take any action, hence both gets a payoff of 0. If $U_{n-1}$ plays $F$; an *uncorrupted* $U_n$ chooses $Ac$ as its best response but a corrupted $U_n$ will choose *Wait & Reject* at $D - \delta$ as its best response since $u_{U_n}(co, W \ \& \ Rt \text{ at time } D - \delta) \geq u_{U_n}(co, F, s''), \forall s'' \in S_{U_n}$. The expected payoff of $U_{n-1}$ for selecting *forward*, denoted as $\mathbb{E}_{U_{n-1}}(F)$, and expected payoff for selecting *not forward*, denoted as $\mathbb{E}_{U_{n-1}}(NF)$ are:

$$\begin{gathered}\mathbb{E}_{U_{n-1}}(F) = \theta(-o_{n-1}^{D-\delta,v+f(v)} - o_{n-1}^{D-\delta,Z_{v+f(v),n-1}}) + (1-\theta)f(\alpha) \\ \mathbb{E}_{U_n}(NF) = 0\end{gathered} \tag{8}$$

Since $\delta \to 0$, we consider $o_{n-1}^{D-\delta,v+f(v)} \approx o_{n-1}^{D,v+f(v)}$ and $o_{n-1}^{D-\delta,Z_{v+f(v),n-1}} \approx o_{n-1}^{D,Z_{v+f(v),n-1}}$. Substituting in Eq. 8, $\mathbb{E}_{U_{n-1}}(F) > \mathbb{E}_{U_n}(NF)$, if $\theta < \frac{f(\alpha)}{f(\alpha)+o_{n-1}^{D,v+f(v)}+o_{n-1}^{D,Z_{v+f(v),n-1}}}$. Hence, $U_{n-1}$ chooses *Forward* if $\theta < \frac{f(\alpha)}{f(\alpha)+o_{n-1}^{D,v+f(v)}+o_{n-1}^{D,Z_{v+f(v),n-1}}}$, else it chooses *Not Forward*; *corrupted* $U_n$ chooses *Wait & Reject* at time $D - \delta$; *uncorrupted* $U_n$ chooses *Accept*; is a perfect Bayesian equilibrium.

*Comparative Static Analysis.* We take the partial derivative of $\mathbb{E}_{U_{n-1}}(F)$ with respect to $\theta$, to observe how the expected payoff of $U_{n-1}$ changes with small change in $\theta$, keeping other variables constant.

$$\frac{\partial \mathbb{E}_{U_{n-1}}(F)}{\partial \theta} = -f(\alpha) - o_{n-1}^{D,v+f(v)} - o_{n-1}^{D,Z_{v+f(v),n-1}} \tag{9}$$

$\frac{\partial \mathbb{E}_{U_{n-1}}(F)}{\partial \theta} < 0$ implies that $\mathbb{E}_{U_{n-1}}(F)$ is a decreasing function upon varying $\theta$. It implies a higher probability of selecting a corrupted node, the expected payoff of $U_{n-1}$ will go down as the probability of facing an attack increases. However, $U_{n-1}$ doesn't lose the channel, unlike in the game $\Gamma_{HTLC}$, where $U_{n-1}$ had to settle on-chain if the corrupted node did not respond. We analyze the effectiveness of *HTLC-GP* in countering griefing attacks in the next section.

### 6.5. *Effectiveness of HTLC-GP*

To avoid paying griefing penalty, $U_n$ cancels the payment just before $D$ elapses i.e., at time $D - \delta$, where $\delta \to 0$ [28]. It is also a form of *congestion attack* [22], where corrupted $U_n$ can continue jamming the network repeatedly just by delaying its decision to resolve the payment. $U_n$ doesn't lose its channel, providing the advantage of mounting the attack repeatedly. Thus, the countermeasure fails to realize the objective of compensating affected parties when the attack is mounted. Let us discuss whether the problem can be solved cryptographically.

*Designing a protocol for compensating uncorrupted parties.* We observe that the parties affected by the attack cannot be compensated if we do not penalize the attacker for each time interval. Since Bitcoin scripting language is not Turing-complete, we cannot have a single off-chain contract where we can define penalty as a function of time.

Given that $D$ is the contract timeout period, let us consider that a party charges penalty after $d$ interval. The timeout period is divided into $\frac{D}{d}$ slots. There must be total $\frac{D}{d}$ cancellation contracts denoted as $C_1, C_2, \ldots, C_{\frac{D}{d}}$. In each contract $C_j$, the penalty locked is $\frac{d}{D} Z_{\alpha_i, i+1}$ and each contract's timeout period is $jd, j \in [1, \frac{D}{d}]$. The problem faced with this construction are as follows:

- It is not desirable to have multiple contracts on a single channel for a single payment. Throughput of the system reduces as channels can accept less payment because of the bound on maximum acceptable HTLCs [43].
- Each cancellation contract has a very short timeout period. This is risky and might compromise with the security of the protocol [22].
- Abrupt closure of channels may not be desired.

Instead of focusing on the cryptographic aspect of the protocol, we focus on the underlying penalization mechanism. We study the effectiveness from the attacker's point of view.

#### 6.5.1. *From attacker's point of view*

The attacker has an objective of maximizing the damage by locking as much network liquidity possible for the given budget $\mathcal{B}_{EX}$. Penalty involves locking extra coins, and it increases the cost of the attack. Once the cost of the attack increases, the attacker will be able to corrupt fewer nodes. We define a metric that measures the coins remaining unutilized in the network.

*Measuring success rate of attack. Capacity locked* in a path routing payment is the summation of the coins locked in the off-chain contract instantiated on the channel forming the path. It is the metric used for measuring the success of the attack from the attacker's point of view [25], [26]. Ignoring the processing fee (negligible quantity), assuming all the payments executed are of value $\alpha$ and the bribe offered per instance is $L$, the attacker can corrupt $\frac{\mathcal{B}_{EX}}{L}$ nodes in the networks.

**Claim 1.** Given the total budget of the attack is $\mathcal{B}_{EX}$, incentive per attack being $L$, transaction value per payment being $\alpha$, HTLC timeout period is $D$, time taken to settle a transaction on-chain being $\Delta$, $n$ is the maximum allowed path length and a corrupted recipient rejects the payment at time $t' = D - \delta$, where $\delta \to 0$, the capacity locked upon using HTLC-GP is less than the capacity locked in HTLC, the loss percent being $\frac{\gamma n(\frac{D}{2} + \frac{\Delta(n-2)}{6})}{1+\gamma n(D + \frac{(n-1)\Delta}{2})}$

Proof: In *HTLC*, a given instance of attack locks $(n-1)\alpha$ coins in the path routing payment. The capacity locked in $\frac{\mathcal{B}_{EX}}{L}(n-1)\alpha$.

In *HTLC-GP*, $U_n$ executes self-payment of amount $v$. It cancels the contract at time $t' = D - \delta$. Capacity locked is $((n-1)v + \sum_{i=1}^{n-1} Z_{v,i})\frac{\mathcal{B}_{EX}}{L}$. In both the cases, we exclude the coins locked by the corrupted node while computing the unusable capacity. We measure the difference in capacity locked to judge the effectiveness.

$$\begin{aligned} &\tfrac{\mathcal{B}_{EX}}{L}(n-1)\alpha - \big(\tfrac{\mathcal{B}_{EX}}{L}(n-1)v + \tfrac{\mathcal{B}_{EX}}{L}\sum_{i=1}^{n-1} Z_{v,i}\big) \\ &= \tfrac{\mathcal{B}_{EX}}{L}((n-1)\alpha - (n-1)v - \sum_{i=1}^{n-1} Z_{v,i}) \end{aligned} \tag{10}$$

Substituting $v = \frac{\alpha}{1+\gamma\sum\limits_{j=0}^{n-1} t_j}$, difference in the capacity locked is $\gamma\frac{\alpha}{1+\gamma(nD+\frac{n(n-1)\Delta}{2})}n(n-1)\frac{\mathcal{B}_{EX}}{L}(\frac{D}{2}+\frac{\Delta(n-2)}{6})$.

The loss percent of capacity locked by the attacker is $\frac{\gamma n(\frac{D}{2}+\frac{\Delta(n-2)}{6})}{1+\gamma n(D+\frac{(n-1)\Delta}{2})}$. The value is greater than 0 for $n \geq 2$. This proves that attacker ends up locking less capacity when HTLC-GP is used as a payment protocol. ■

*Inference.* Initially, $\gamma$ can be set very low. If the incidence of griefing attack increases, then $\gamma$ can be increased. However, the disadvantage of increasing the penalty means uncorrupted nodes have to put a higher amount at stake for routing small valued payments. The success rate of payments decreases due to a lack of liquidity in the channels. Thus, the network may stick to using a low value of $\gamma$ even though it may remain at the risk of facing a higher incidence of griefing attack. Depending on the factor $\gamma$, if the loss percent is not substantial, then the attacker can still go ahead with corrupting the nodes in the network. Hence, the payment protocol *HTLC-GP* is *weakly effective* in disincentivizing the attack.

## 7. Guaranteed Minimum Compensation for further disincentivizing Griefing Attack

Our objective is to increase the cost of the attack without forcing uncorrupted parties to lock high penalties. It will be possible if the maximum path length allowed for routing of payments is decreased. [22] suggested that controlling the maximum path length for routing payments increases the cost of the attack. However, they have not stated how one can control the path length. If maximum path length becomes a system parameter, then an abrupt reduction in path length may lead to higher failure in executing transactions. For ease of analysis, we ignore the processing fee charged by each intermediate party.

Compensation offered to a party may be too low for a given rate of penalty in HTLC-GP. A low rate under-compensates affected parties, whereas a higher rate reduces the liquidity in the network. A trade-off is achieved by setting a threshold on the compensation offered by an off-chain contract. For a given rate of penalty, the maximum cumulative penalty, denoted as $Z_{\alpha,max}$ that $U_n$ is required to lock, is $\gamma\alpha\sum_{i=1}^{n}(D+(n-i)\Delta)$. Let us denote $\gamma\sum_{i=1}^{n}(D+(n-i)\Delta)$ as $k$, where $k \in \mathbb{R}^+$. Thus, we have $Z_{\alpha,max} = k\alpha$. We introduce a new parameter $\zeta$, termed as ***Guaranteed Minimum Compensation***. The major source of earning of a node is from the processing fee by routing transactions. Based on the data provided [44], the fee earned by each node on a single day is quite low compared to the amount routed. Thus, we set $\zeta$ in the range $[0,1)$ to avoid over-compensation.

### *7.1. Adjusting Maximum Path Length*

The factor $\zeta$ is dependent on the belief $\theta$. If the probability of a node being corrupted is high, then parties routing payment will demand higher compensation in order to disincentivize the attacker. We estimate the maximum allowed path length, $\tilde{n}$, for routing payments when a minimum threshold on compensation is imposed.

**Proposition 1.** Given the maximum cumulative griefing-penalty for a payment $\alpha$ is $k\alpha$, and the guaranteed minimum compensation $\zeta$, the maximum path length for routing transaction is $\frac{k}{\zeta}$.

Proof: In *HTLC-GP*, $Z_{\alpha,max} = k\alpha$. Upon introduction of *guaranteed minimum compensation*, any node routing a payment $\alpha$ is entitled to a minimum compensation $\zeta\alpha$ upon being affected by the griefing attack. If the compensation falls below this amount, the node will refuse to forward the contract. Thus, the recipient must bear a cumulative penalty of at least $\zeta\tilde{n}\alpha$ for a path of length $\tilde{n}$. Thus, the following criteria must hold:

$$\begin{aligned} &\tilde{n}\zeta\alpha \leq Z_{\alpha,max} \\ &or, \tilde{n}\zeta\alpha \leq k\alpha \\ &or, \tilde{n} \leq \frac{k}{\zeta} \end{aligned} \tag{11}$$

Thus the maximum path length in HTLC-GP$^{\zeta}$ is $\frac{k}{\zeta}$. ■

If the incidence of griefing attack increases, then the maximum allowed path length can be decreased by increasing $\zeta$.

### *7.2. Estimating Rate of Griefing-Penalty $\gamma^{\zeta,k}$*

Once the maximum path length is adjusted, the rate of griefing-penalty $\gamma$ is no more a free variable that can be set too high or too low. Given that $k\alpha$ is the maximum cumulative penalty for routing a payment of $\alpha$, and the path length decreases from $n$ to $\tilde{n}$ then $\gamma$ must be increased. We call this new rate of griefing-penalty $\gamma^{\zeta,k}$ and calculate the rate of griefing-penalty based on these factors.

**Proposition 2.** Given $\zeta$ as the guaranteed minimum compensation, ratio of maximum cumulative griefing penalty and the transaction amount is $k$, and the least timeout period of the off-chain contract being $D$, the rate of griefing-penalty $\gamma^{\zeta,k}$ is $\frac{2\zeta^2}{2\zeta D+\Delta(k-\zeta)}$.

Proof: Using the value of $Z_{\alpha,max} = k\alpha$ and maximum path length for routing is $\tilde{n}$, we estimate $\gamma^{\zeta,k}$:

$$\begin{aligned} k\alpha &= \gamma^{\zeta,k} \textstyle\sum_{i=1}^{\tilde{n}} (D + (\tilde{n}-i)\Delta)\alpha \\ or, \quad \gamma^{\zeta,k} &= \frac{k}{\Delta\tilde{n}(\frac{D}{\Delta}+\frac{\tilde{n}-1}{2})} \end{aligned} \tag{12}$$

Replacing $\tilde{n}$ by the expression given in Proposition 1, we have $\gamma^{\zeta,k} = \frac{2\zeta^2}{2\zeta D+\Delta(k-\zeta)}$. ■

## 8. Modifying HTLC-GP to HTLC-GP$^{\zeta}$

In this section, we discuss the modified payment protocol HTLC-GP$^{\zeta}$. The corrupted node can still mount the attack without paying any penalty. However, our objective is to disincentivize the attacker by abruptly decreasing the capacity locked.

### *8.1. Protocol Description*

For relaying funds from $U_0$ to $U_{\tilde{n}}$, both of them decides on $k$ for a given $\zeta$ and sets $\tilde{n}$. The rate of griefing-penalty $\gamma^{\zeta,k}$ is calculated accordingly for a given HTLC timeout period $D$. The total amount that the payer needs to transfer is $\tilde{\alpha} = \alpha + (\tilde{n}-1)f(\alpha)$. We denote each $\alpha_i = \tilde{\alpha} - if(\alpha), i \in [0, \tilde{n}-1], \alpha_0 = \tilde{\alpha}$. Each node $U_i$ samples a pair of secret key and public key $(sk_i, pk_i)$, the public key of each node is used to encrypt the information of establishing contract with the neighboring node. An off-chain contract between $U_i$ and $U_{i+1}$ has a timeout period of $t_i$. $t_{\tilde{n}-1}$ is set to $D$. We discuss the various phases of the modified version of payment protocol, the description being similar to *HTLC-GP* [15].

`Pre-processing Phase`

$U_0$ must not use the exact path for routing payment. If the exact path length is used, $U_1$ locks a penalty $\gamma^{\zeta,k}\alpha_0 t_0$ with $U_0$, it can easily figure out the identity of the sender, violating privacy. Thus, it randomizes the exact path length using a random function $\phi$, and shares $\phi(\tilde{n})$ with $U_{\tilde{n}}$. The latter calculates the cumulative penalty $\gamma^{\zeta,k}\phi(\tilde{n})\alpha D$ used for establishing the *cancellation contract.*

*Calculating $\phi(\tilde{n})$.* A routing attempt cost $\psi$ is added such that $\gamma^{\zeta,k}\phi(\tilde{n})\alpha D \approx \gamma^{\zeta,k}((\psi+\alpha_0)t_0 + \Sigma_{j=1}^{\tilde{n}-1}\alpha_j t_j)$. This acts like a blinding factor and $U_1$ cannot infer the identity of the sender from the penalty it locks in the off-chain contract formed with $U_0$. The following steps are executed next:

- $U_{\tilde{n}}$ samples two random numbers $x$ and $r$ where $x \neq r$. It constructs the payment hash $H = \mathcal{H}(x)$ and the cancellation hash $Y = \mathcal{H}(r)$.
- The payee shares both the hashes $H$ and $Y$ with the payer $U_0$.
- The cumulative griefing-penalty to be locked by $U_1$ is $\text{cgp}_0 = \gamma^{\zeta,k}(\psi + \tilde{\alpha})t_0$. The cumulative griefing-penalty to be locked by any other node $U_{i+1}, i \in [1, \tilde{n}-1]$ is $\text{cgp}_i = \gamma^{\zeta,k}.(\Sigma_{j=1}^{i}(\alpha_j t_j) + (\alpha_0 + \psi)t_0)$.
- The payer uses standard onion routing [45] for propagating the information needed by each node $U_i, i \in [1, \tilde{n}]$, across the path $P$. $U_0$ sends $M_0 = E(\dots E(E(E(\phi, Z_{\tilde{n}}, pk_{\tilde{n}}), Z_{\tilde{n}-1}, pk_{\tilde{n}-1}), Z_{\tilde{n}-2}, pk_{\tilde{n}-2})\dots, Z_1, pk_1)$ to $U_1$, where $Z_i = (H, Y, \alpha_i, t_{i-1}, \text{cgp}_{i-1}, U_{i+1}), i \in [1, \tilde{n}-1]$ and $Z_{\tilde{n}} = (H, Y, \alpha_{\tilde{n}-1}, t_{\tilde{n}-1}, \text{cgp}_{\tilde{n}-1}, null)$. Here $M_{i-1} = E(M_i, Z_i, pk_i)$ is the encryption of the message $M_i$ and $Z_i$ using public key $pk_i$, $M_{\tilde{n}} = \phi$.
- $U_1$ decrypts $M_0$, gets $Z_1$ and $M_1$. $M_1 = E(\dots E(E(E(\phi, Z_{\tilde{n}}, pk_{\tilde{n}}), Z_{\tilde{n}-1}, pk_{\tilde{n}-1}), Z_{\tilde{n}-2}, pk_{n-2}), \dots, Z_2, pk_2)$ is forwarded to the next destination $U_2$. This continues till party $U_{\tilde{n}}$ gets $E(\phi, Z_{\tilde{n}}, pk_{\tilde{n}})$.

`Two-Round Locking Phase` It involves two rounds: *establishing Cancellation Contract* and *establishing Payment Contract.*

- *Establishing Cancellation Contract*: $U_{\tilde{n}}$ initiates this round and each player $U_i, i \in [1, \tilde{n}]$ locks their respective cumulative griefing-penalty $cgp_{i-1}$.
  - $U_{\tilde{n}}$ decrypts and gets $Z_{\tilde{n}}$. It checks $\gamma^{\zeta,k}\phi(\tilde{n})\alpha D \overset{?}{=} cgp_{\tilde{n}-1}$ and $\alpha_{\tilde{n}-1} \overset{?}{=} \alpha$. If this holds true, the payer forms a contract with $U_{\tilde{n}-1}$, locking $cgp_{\tilde{n}-1}$.
  - For any other party $U_i, i \in [1, \tilde{n}-1]$, it first checks $cgp_i - \gamma^{\zeta,k}\alpha_i t_i \overset{?}{=} cgp_{i-1}$. This ensures that there is sufficient coins to be locked as penalty in the contract to be formed with $U_{i-1}$. Next, it checks $\gamma^{\zeta,k}\alpha_i t_i \geq \zeta\alpha_i$. This check ensures that $U_i$ is guaranteed a minimum compensation upon being affected by griefing attack. If both the condition satifies, $U_i$ forms the off-chain contract with $U_{i-1}$, locking $cgp_{i-1}$.
  - The off-chain contract for locking penalty in layman terms: *'$U_{i+1}$ can withdraw the amount $cgp_i = \gamma^{\zeta,k}.(\Sigma_{j=1}^{i}(\alpha_j t_j) + (\alpha_0 + \psi)t_0)$ from the contract contingent to the release of either $x : H = \mathcal{H}(x)$ or $r : Y = \mathcal{H}(r)$ within time $t_i$. If the locktime elapses and $U_{i+1}$ does not respond, $U_i$ claims $cgp_i$ after the locktime elapses.'*.

  The pseudocode of the first round of Locking Phase for $U_{\tilde{n}}$, any intermediate party $U_i, i \in [1, \tilde{n}-1]$ and payer $U_0$ is stated in Procedure 1, Procedure 2 and Procedure 3 respectively.

- *Establishing Payment Contract*: $U_0$ initiates the next rounded provided it has received the cancellation contract and $cgp_0 \geq \zeta\alpha_0$. The conditional payment is forwarded till it reaches the payer $U_{\tilde{n}}$. This proceeds as normal *HTLC*.
  - Each node $U_i, i \in [0, \tilde{n}-1]$ checks that for a belief $\theta_i$ regarding $U_{i+1}$'s type, the expected payoff on forwarding the contract is greater than 0. If so, it forwards the terms of the off-chain contract to $U_{i+1}$, locking $\alpha_i$ coins.
  - The off-chain contract for payment in layman terms: *'$U_{i+1}$ can claim $\alpha_i$ coins contingent to the release of $x : H = \mathcal{H}(x)$ within time $t_i$. If $U_{i+1}$ does not respond, $U_i$ unlocks $\alpha_i$ coins from the contract either by releasing preimage $r : Y = \mathcal{H}(r)$ or after the locktime elapses.'*

**Procedure 1:** Establishing Cancellation Contract: First Round of Locking Phase for $U_{\tilde{n}}$

```
1  Input: $(Z_{\tilde{n}}, \phi(\tilde{n}), \gamma^{\zeta,k}, \alpha)$
2  $U_{\tilde{n}}$ parses $Z_{\tilde{n}}$ and gets $H', Y', \alpha', t', \mathrm{cgp}_{\tilde{n}-1}$.
3  if $t' \geq t_{now} + \Delta$ and $\alpha' \overset{?}{=} \alpha$ and $k\alpha \overset{?}{=} cgp_{\tilde{n}-1}$ and $H' \overset{?}{=} H$ and $Y' \overset{?}{=} Y$ and
     $remain(U_{\tilde{n}}, U_{\tilde{n}-1}) \geq cgp_{\tilde{n}-1}$ then
4      Send Cancel_Contract_Request$(H, Y, t', \mathrm{cgp}_{\tilde{n}-1}, \gamma^{\zeta,k})$ to $U_{\tilde{n}-1}$
5      if acknowledgement received from $U_{\tilde{n}-1}$ then
6          $remain(U_{\tilde{n}}, U_{\tilde{n}-1}) = remain(U_{\tilde{n}}, U_{\tilde{n}-1}) - \mathrm{cgp}_{\tilde{n}-1}$
7          establish $Cancel\_Contract(H, Y, t', \mathrm{cgp}_{\tilde{n}-1})$ with $U_{\tilde{n}-1}$
8          Record $t_{\tilde{n}}^{form} = current\_clock\_time$
9      end
10     else
11         abort
12     end
13 end
14 else
15     abort.
16 end
```

**Procedure 2:** Establishing Cancellation Contract: First Round of Locking Phase for $U_i, i \in [1, n-1]$

```
1  Input: $(H', Y', t', \mathrm{cgp}_i, \gamma^{\zeta,k})$
2  $U_i$ parses $Z_i$ and gets $H, Y, \alpha_i, t_{i-1}, \mathrm{cgp}_{i-1}$.
3  if $H' \overset{?}{=} H$ and $Y \overset{?}{=} Y'$ and $t' + \Delta \overset{?}{\leq} t_{i-1}$ and $cgp_i - \gamma^{\zeta,k}\alpha_i t' \overset{?}{=} cgp_{i-1}$ and $\gamma^{\zeta,k}\alpha_i t' \geq \zeta\alpha_i$ and
     $remain(U_i, U_{i+1}) \geq \alpha_i$ and $remain(U_i, U_{i-1}) \geq cgp_{i-1}$ and (current_time not close to contract
     expiration time) then
4      Sends acknowledgment to $U_{i+1}$ and wait for the off-chain contract to be established
5      Send Cancel_Contract_Request$(H, Y, t_{i-1}, \mathrm{cgp}_{i-1}, \gamma^{\zeta,k})$ to $U_{i-1}$
6      if acknowledgement received from $U_{i-1}$ then
7          $remain(U_i, U_{i-1}) = remain(U_i, U_{i-1}) - \mathrm{cgp}_{i-1}$
8          establish $Cancel\_Contract(H, Y, t_{i-1}, \mathrm{cgp}_{i-1})$ with $U_{i-1}$
9      end
10     else
11         abort
12     end
13 end
14 else
15     abort.
16 end
```

**Procedure 3:** Establishing Cancellation Contract: First Round of Locking Phase for $U_0$

```
Input: $(H', Y', t', \text{cgp}', \gamma^{\zeta,k})$
if $t' \overset{?}{=} t_0$ and $cgp' \overset{?}{=} cgp_0 \geq \zeta\alpha_0$ and $H' \overset{?}{=} H$ and $Y' \overset{?}{=} Y$ and $remain(U_0, U_1) \geq \alpha_0$ then
    Sends acknowledgment to $U_1$
    Confirm formation of penalty contract with $U_1$
    Initiate the second round, the establishment of payment contract
end
else
    abort.
end
```

**Procedure 4:** Establishing Payment Contract: Second Round of Locking Phase for $U_0$

```
Input: $(H, Y, \alpha_0, t_0)$
if $\theta_0 < \frac{1}{1+o^{t_0, g(\alpha)}}$ and ($U_1$ has agreed to form the contract) and (current_time not close to contract expiration time) then
    $remain(U_0, U_1) = remain(U_0, U_1) - \alpha_0$
    establish $Payment\_Contract(H, Y, t_0, \alpha_0)$ with $U_1$
end
else
    abort
end
```

**Procedure 5:** Establishing Payment Contract: Second Round of Locking Phase for $U_i, i \in [1, n-1]$

```
Input: $(H, Y, \alpha_i, t_i)$
if $\theta_i < \frac{f(\alpha)}{f(\alpha)+o_i^{t_i, \alpha+(\tilde{n}-i)f(\alpha)}}$ and $t_{i-1} \geq t_i + \Delta$ and $\alpha_i \overset{?}{=} \alpha_{i-1} + fee(U_i)$ and ($U_{i+1}$ has agreed to form the contract) and (current_time not close to contract expiration time) then
    $remain(U_i, U_{i+1}) = remain(U_i, U_{i+1}) - \alpha_i$
    establish $Payment\_Contract(H, Y, t_i, \alpha_i)$ with $U_{i+1}$
end
else
    abort
end
```

The pseudocode of the second round of Locking Phase for $U_0$ and any intermediate party $U_i, i \in [1, \tilde{n}-1]$ is stated in Procedure 4 and Procedure 5 respectively.

<u>`Release Phase`</u>: $U_{\tilde{n}}$ waits for $\mu$ units of time before deciding either accepting or canceling the payment. If the payment contract received from $U_{\tilde{n}-1}$ is correct, $U_{\tilde{n}}$ releases the preimage $x$ for payment hash $H$ and claims the coins from $U_{\tilde{n}-1}$. If the latter has not forwarded the conditional payment, or the payer has encountered an error (wrong payment or penalty value, invalid lock time) in the terms stated in the incoming off-chain contract, $U_{\tilde{n}}$ releases the cancellation preimage $r$. In case of dispute, the payer goes on-chain and releases one of the preimages for settling the contract. The rest of the parties $U_i, i \in [1, \tilde{n}-1]$ either claim the coins or cancel the payment based on the preimage released. If $U_{i+1}$ griefs and refuses to release preimage to $U_i$, the former has to pay the cumulative griefing-penalty $cgp_i$ for affecting the nodes $U_k, 0 \leq k \leq i$, so that all the nodes obtain their due compensation.

The pseudocode of the Release Phase for $U_{\tilde{n}}$ and any intermediate party $U_i, i \in [1, \tilde{n}-1]$ is stated in Procedure 6 and Procedure 7 respectively.

## *8.2. Effectiveness of HTLC-GP$^{\zeta}$*

Even in HTLC-GP$^{\zeta}$, a corrupted node can still mount the attack by canceling the payment just before the off-chain contract's lock time elapses. Thus we study the effectiveness of the countermeasure from the attacker's point of view with *capacity locked* in the network as the metric.

**Claim 2.** Given the total budget of the attack is $\mathcal{B}_{EX}$, incentive per attack being $L$, transaction value per payment being $\alpha$, HTLC timeout period is $D$, time taken to settle a transaction on-chain being $\Delta$, $n$ is the maximum allowed path length for HTLC, $\tilde{n}$ is the maximum allowed path length for HTLC-GP$^{\zeta}$ and a corrupted recipient rejects the payment at time $t' = D - \mu$, where $\mu \to 0$, the capacity locked in HTLC-GP$^{\zeta}$ is less than the capacity locked in HTLC, the loss percent being $\frac{n-\tilde{n}}{(n-1)\left(1+\gamma^{\zeta,k}nD+\gamma^{\zeta,k}n\Delta\frac{n-1}{2}\right)} + \frac{\gamma^{\zeta,k}\tilde{n}((n-1)(D+\frac{(\tilde{n}-1)\Delta}{2})-\frac{\tilde{n}-1}{2}(D+\frac{(2\tilde{n})\Delta}{3}))}{(n-1)\left(1+\gamma^{\zeta,k}nD+\gamma^{\zeta,k}n\Delta\frac{n-1}{2}\right)}$

Proof: In HTLC-GP$^{\zeta}$, the capacity locked is $((\tilde{n}-1)v + \sum_{i=1}^{\tilde{n}-1} Z_{v,i})\frac{\mathcal{B}_{EX}}{L}$. In both the cases, we exclude the coins locked by the corrupted node while computing the capacity locked. We measure the difference in capacity locked in *HTLC* and HTLC-GP$^{\zeta}$.

$$\begin{aligned}
&\tfrac{\mathcal{B}_{EX}}{L}(n-1)\alpha - \tfrac{\mathcal{B}_{EX}}{L}((\tilde{n}-1)v + \sum_{i=1}^{\tilde{n}-1} Z_{v,i}) \\
&= \tfrac{\mathcal{B}_{EX}}{L}\Big((n-1)\alpha - ((\tilde{n}-1)v + \sum_{i=1}^{\tilde{n}-1} Z_{v,i})\Big) \\
&= \tfrac{\mathcal{B}_{EX}}{L}\Big((n-1)v(1+\gamma^{\zeta,k}\sum_{j=1}^{\tilde{n}} t_j) - ((\tilde{n}-1)v + \sum_{i=1}^{\tilde{n}-1} Z_{v,i})\Big) \\
&= v\tfrac{\mathcal{B}_{EX}}{L}\Big((n-\tilde{n}) + \gamma^{\zeta,k}\tilde{n}((n-1)(D+\tfrac{(\tilde{n}-1)\Delta}{2}) - \tfrac{\tilde{n}-1}{2}(D+\tfrac{(2\tilde{n}-1)\Delta}{3}))\Big)
\end{aligned} \tag{13}$$

The loss percent is ratio of difference of collateral locked in HTLC and HTLC-GP$^{\zeta}$ and collateral locked in HTLC.

$$\frac{v\frac{\mathcal{B}_{EX}}{L}\Big((n-\tilde{n})+\gamma^{\zeta,k}\tilde{n}((n-1)(D+\frac{(\tilde{n}-1)\Delta}{2})-\frac{\tilde{n}-1}{2}(D+\frac{(2\tilde{n}-1)\Delta}{3}))\Big)}{\frac{\mathcal{B}_{EX}}{L}(n-1)\alpha} \tag{14}$$

Considering $t_{n-1} = D$ and $t_i = D + (n-i-1)\Delta, i \in [0, n-1]$, where $\sum_{j=0}^{n-1} t_j = nD + \frac{n(n-1)}{2}\Delta$ and substituting $\alpha = v(1 + \gamma^{\zeta,k} \sum_{j=0}^{n-1} t_j)$, the loss percent is

$$\begin{aligned} &\frac{v\frac{\mathcal{B}_{EX}}{L}\left((n-\tilde{n})+\gamma^{\zeta,k}\tilde{n}((n-1)(D+\frac{(\tilde{n}-1)\Delta}{2})-\frac{\tilde{n}-1}{2}(D+\frac{(2\tilde{n}-1)\Delta}{3}))\right)}{\frac{\mathcal{B}_{EX}}{L}(n-1)v(1+\gamma^{\zeta,k}\sum_{j=0}^{n-1}t_j)} \\ &= \frac{n-\tilde{n}}{(n-1)\left(1+\gamma^{\zeta,k}nD+\gamma^{\zeta,k}n\Delta\frac{n-1}{2}\right)} + \frac{\gamma^{\zeta,k}\tilde{n}((n-1)(D+\frac{(\tilde{n}-1)\Delta}{2})-\frac{\tilde{n}-1}{2}(D+\frac{(2\tilde{n})\Delta}{3}))}{(n-1)\left(1+\gamma^{\zeta,k}nD+\gamma^{\zeta,k}n\Delta\frac{n-1}{2}\right)} \end{aligned} \tag{15}$$

■

*Inference.* The loss percent is dominated by the factor $\frac{n-\tilde{n}}{n-1}$. For a given $k$, the higher the factor $\zeta$, lower is the maximum path length $\tilde{n}$, greater is the loss incurred.

**Procedure 6:** Release_Phase for $U_{\tilde{n}}$

```
1  Input: Message $M$, time bound $\mu$
2  if $M \overset{?}{=} Payment\_Contract(H, Y, \alpha', t')$ and $current\_clock\_time - t_{\tilde{n}}^{form} \leq \mu$ then
3      Parse $M$ and retrieve $(H, Y, \alpha', t')$
4      if $t' \geq t_{now} + \Delta$ and $\alpha' = \alpha$ then
5          $z = x$
6      end
7      else
8          $z = r$
9      end
10 end
11 else
12     $z = r$
13 end
14 Release $z$ to $U_{\tilde{n}-1}$
15 if $current\_time < t_{\tilde{n}-1}$ then
16     if $U_{\tilde{n}}$ and $U_{\tilde{n}-1}$ mutually agree to terminate Payment Contract and Cancellation Contract then
17         if $z{=}x$ then
18             $remain(U_{\tilde{n}}, U_{\tilde{n}-1}) = remain(U_{\tilde{n}}, U_{\tilde{n}-1}) + \alpha + \text{cgp}_{\tilde{n}-1}$
19         end
20         else
21             $remain(U_{\tilde{n}}, U_{\tilde{n}-1}) = remain(U_{\tilde{n}}, U_{\tilde{n}-1}) + \text{cgp}_{\tilde{n}-1}$
22             $remain(U_{\tilde{n}-1}, U_{\tilde{n}}) = remain(U_{\tilde{n}-1}, U_{\tilde{n}}) + \alpha$
23         end
24     end
25     else
26         $U_{\tilde{n}}$ goes on-chain for settlement by releasing preimage $z$.
27     end
28 end
29 else
30     $U_{\tilde{n}-1}$ goes on-chain for settlement, claims $(\alpha + \text{cgp}_{\tilde{n}-1})$.
31     $z = null$
32 end
33 Call Release_Phase($U_{\tilde{n}-1}, z$)
```

**Procedure 7:** Release_Phase for $U_i, i \in [1, \tilde{n} - 1]$

```
Input: $z$
Release $z$ to $U_{i-1}$
if $z \neq null$ and $current\_time < t_{i-1}$ then
    if $U_i$ and $U_{i-1}$ mutually agree to terminate Payment Contract and Cancellation Contract then
        if $z = x$ then
            $remain(U_i, U_{i-1}) = remain(U_i, U_{i-1}) + \alpha_{i-1} + \text{cgp}_{i-1}$
        end
        else
            $remain(U_i, U_{i-1}) = remain(U_i, U_{i-1}) + \text{cgp}_{i-1}$
            $remain(U_{i-1}, U_i) = remain(U_{i-1}, U_i) + \alpha_{i-1}$
        end
    end
    else
        $U_i$ goes on-chain for settlement by releasing preimage $z$.
    end
end
else
    $U_{i-1}$ goes on-chain for settlement after elapse of locktime $t_{i-1}$, claims $(\alpha_{i-1} + \text{cgp}_{i-1})$.
end
Call Release_Phase($U_{i-1}, z$)
```

## 9. Experimental Analysis

### *9.1. Setup*

For our experiments, we use Python 3.8.2 and NetworkX, version 2.4 [46]. It is a Python package for analyzing complex networks. System configuration used is Intel Core i5-8250U CPU, Operating System: Kubuntu 20.04, Memory: 7.7 GiB of RAM. The code for our implementation is available on GitHub[6]. From the dataset mentioned in [22], twelve snapshots of Bitcoin Lightning Network taken over a year, starting from *September 2019*, have been used. Each snapshot provides information regarding the public key of the nodes and the aliases used. The network is represented in the form of channels, as a pair of public keys along with the channel capacity and the channel identifier. Since our proposed strategy for countering griefing attacks requires both the parties to fund the channel, we divide the capacity of the channel into equal halves, allocating each half as the balance of a counterparty.

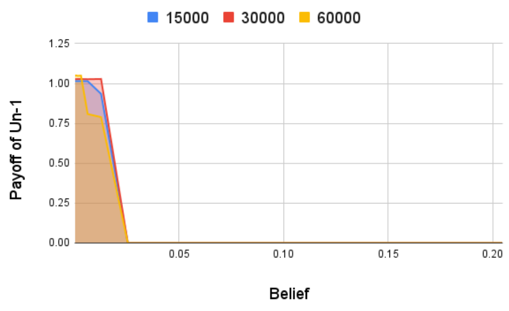
### *9.2. Evaluation Methodology*

*Attacking Strategy*: The attacker corrupts the node, which are pendant vertices or nodes having just one channel in the network. It is easier and cost-effective to target such peripheral nodes rather than nodes with high centrality. Highly central nodes tend to make a higher profit as transactions tend to get routed through such nodes. Also, the attacker needs to offer a higher incentive per attack, which may not be a good strategy. On the other hand, peripheral nodes can be easily incentivized to deviate, as they haven't gained much trust in the network. They do not expect to earn much by behaving altruistically.

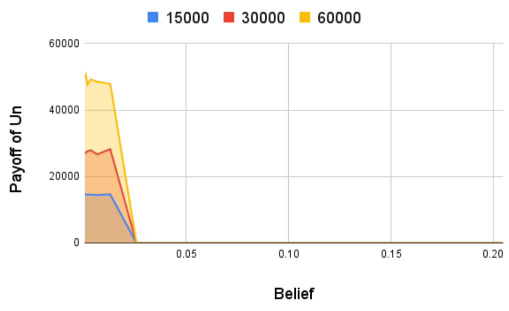
For the simulation, we divide this section into three parts:

- (i) The first part analyzes the payoff of each party involved in the games $\Gamma_{HTLC}$ and $\Gamma_{HTLC-GP}$. We simulate the games $\Gamma_{HTLC}$ and, $\Gamma_{HTLC-GP}$ respectively, and estimate the payoff of $U_{n-1}$ and $U_n$. We consider a *Poisson distribution* for the arrival of transaction in a given channel [39]. The rate of

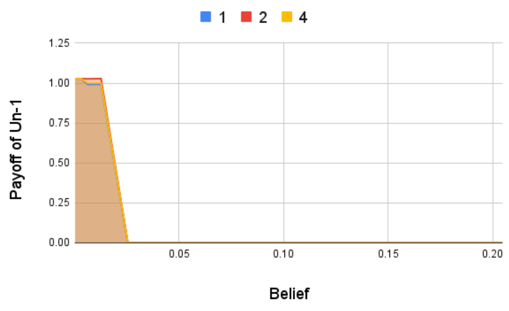
[6]`https://github.com/subhramazumdar/Strategic_Analysis_Griefing`



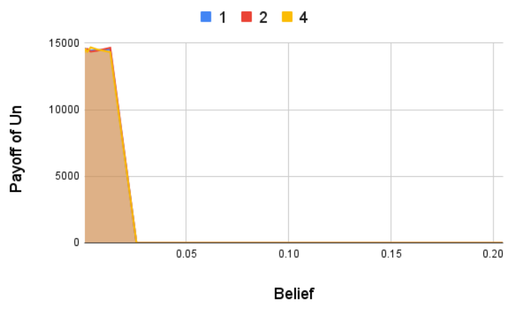
(a) Payoff of $U_{n-1}$, varying transaction value



(b) Payoff of $U_n$, varying transaction value



(c) Payoff of $U_{n-1}$, varying rate of arrival of transaction



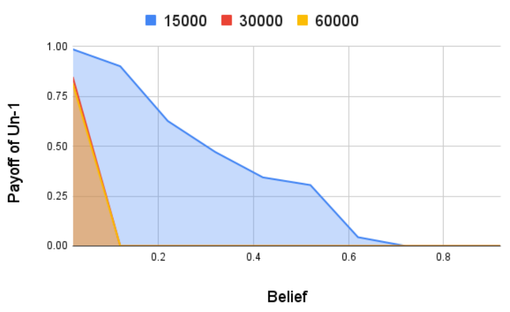
(d) Payoff of $U_n$, varying rate of arrival of transaction

Figure 6: Simulation of $\Gamma_{HTLC}$

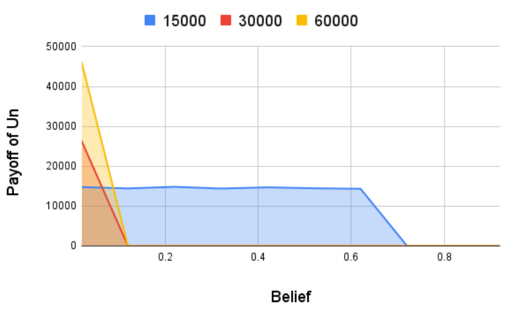
arrival of the transaction is varied between 1 and 4 for the next 10 *blocks*. The path length is set 20 and $D = 100$. The transaction amount is varied between 15000 satoshis to 60000 satoshis. The mining fee for closing a channel is 0.00000154 $BTC$[7]. $q$ is set to 0.7. If the coins remaining unutilized are $C$, the party tries to estimate the fee earned in the future had it utilized the coins. We set $per\_tx\_val$ to 1000 satoshis, thus a party will earn by processing $\frac{C}{1000}$ transactions.

- (ii) $HTLC-GP$: The second part analyses the decrease in capacity locked when a penalty is introduced. We also analyze the rate of the successful transaction when $\gamma$ is varied. Since excess capacity gets locked upon increasing $\gamma$, we expect the channels to drop transaction requests due to lack of liquidity. The transaction value is varied between 10000 satoshis to 100000 satoshis. $\gamma$ is varied between $10^{-3}$ to $10^{-7}$.
  - (a) The budget of the attacker is varied between 0.05 $BTC - 6.25$ $BTC$. The path length is set to 20 and $D$ is set to 100.
  - (b) This set of experiments analyzes the rate of the successful transaction when there is no griefing attack. We vary the number of transactions between 3000-9000 and path length is varied between 5 and 20.
- (iii) $HTLC-GP^{\zeta}$: The third part analyses the further decrease in capacity locked upon introduction of penalty, as well as guaranteed minimum compensation in the payment protocol for a given budget of the attacker. The budget of the attacker is varied between 0.05 $BTC - 6.25$ $BTC$. The transaction

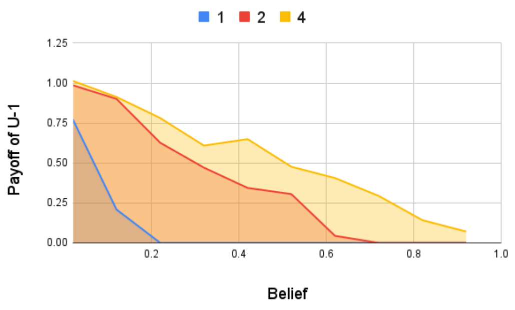
[7]We have considered the data for mining fee observed for one particular channel closure `https://blockstream.info/tx/c0471c9ff72a883aa45058029049ffa12b92d7379f44447bc1df52382c725c01`, the mining fee can vary as observed for various closed channels in `https://1ml.com/channel?order=closedchannels`



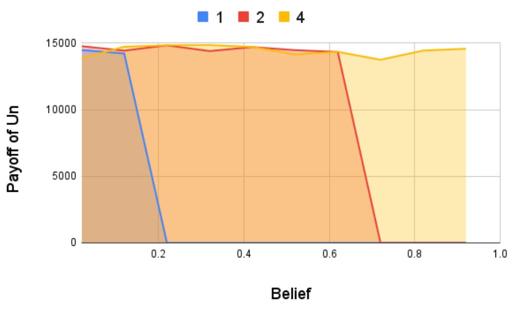
(a) Payoff of $U_{n-1}$, varying transaction value



(b) Payoff of $U_n$, varying transaction value



(c) Payoff of $U_{n-1}$, varying rate of arrival of transaction



(d) Payoff of $U_n$, varying rate of arrival of transaction

Figure 7: Simulation of $\Gamma_{HTLC-GP}$

value is varied between 10000 satoshis to 100000 satoshis. We vary the parameter $k$ between 0.005 to 2. For a fixed $k$, $\zeta$ is varied so that path length ranges between 2 to 20. Both $D$ and $\Delta$ are set to 100.

## *9.3. Simulation Result*

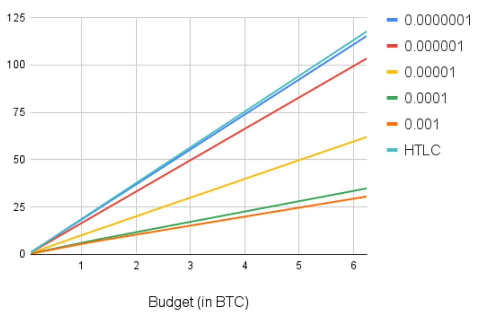
- *Expected Payoff*:
  - $\Gamma_{HTLC}$: For transaction value ranging $15000 - 60000$ (in satoshis) and rate of arrival of transaction fixed to 10 within 10 blocks , the plots in Fig. 6(a) and 6(b) shows the expected payoff of $U_{n-1}$ and expected payoff of $U_n$ varying with the belief $\theta$. $U_{n-1}$'s payoff decreases with increase in $\theta$, confirming the theoretical result provided in *Comparative Static Analysis* in Section 4.4. Payoff of $U_n$ remains more or less constant for a fixed transaction amount, but increases with increase in the transaction amount. For $\theta \geq 0.025$, $U_{n-1}$ acts cautious and chooses *not forward*, as forwarding will lead to negative payoff. Both $U_{n-1}$'s and $U_n$'s payoff drops to 0 from this point onwards.

    In Fig. 6(c) and 6(d), the rate of arrival of transaction is varied between 1 and 4 within a period of 10 blocks and transaction amount is 15000 satoshi. We observe that for $\theta < 0.025$, payoff of $U_{n-1}$ and $U_n$ remains positive and invariant.

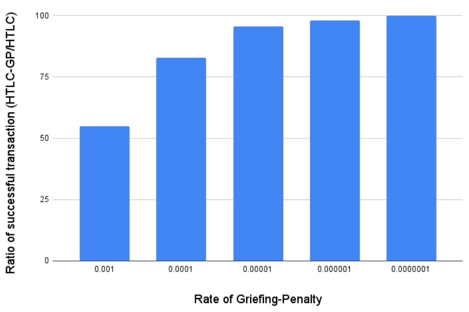
- $\Gamma_{HTLC-GP}$: The plots in Fig. 7(a) and 7(b) shows that for $\theta \geq 0.1$, $U_{n-1}$ acts cautious and chooses *not forward* for transaction varying between 30000 satoshi and 60000 satoshis. For transaction amount 15000, expected payoff of $U_{n-1}$ and $U_n$ remains positive till $\theta < 0.7$.

  In Fig. 7(c) and 7(d), given the rate of arrival of transaction is 1, $U_{n-1}$ chooses to *forward* till $\theta \leq 0.2$. When the rate of arrival of transaction is 2, $U_{n-1}$ chooses to *forward* till $\theta \leq 0.7$ and when rate of arrival is 4, $\theta \leq 0.9$.

- *HTLC-GP*: We discuss our observation for HTLC-GP:



(a) Capacity locked (in BTC) vs Adversary's Budget



(b) Ratio of successful transaction (HTLC-GP/HTLC) upon varying $\gamma$

Figure 8: $\gamma$ is varied between $10^{-3}$ to $10^{-7}$

- The capacity locked drops from 90% to 20% when $\gamma$ is varied between $10^{-7}$ to $10^{-3}$ as shown in Fig.8(a). We see a sharp decrease in capacity locked when $\gamma$ increases from $10^{-6}$ to $10^{-5}$, with the capacity, locked dropping from 82% to 50%. When $\gamma$ is $10^{-4}$, the capacity locked drops to 25%.
- In Fig.8(b), the ratio of successful transaction executed drops to 54% when $\gamma$ is $10^{-3}$ and it is around 99% when $\gamma$ is $10^{-7}$.

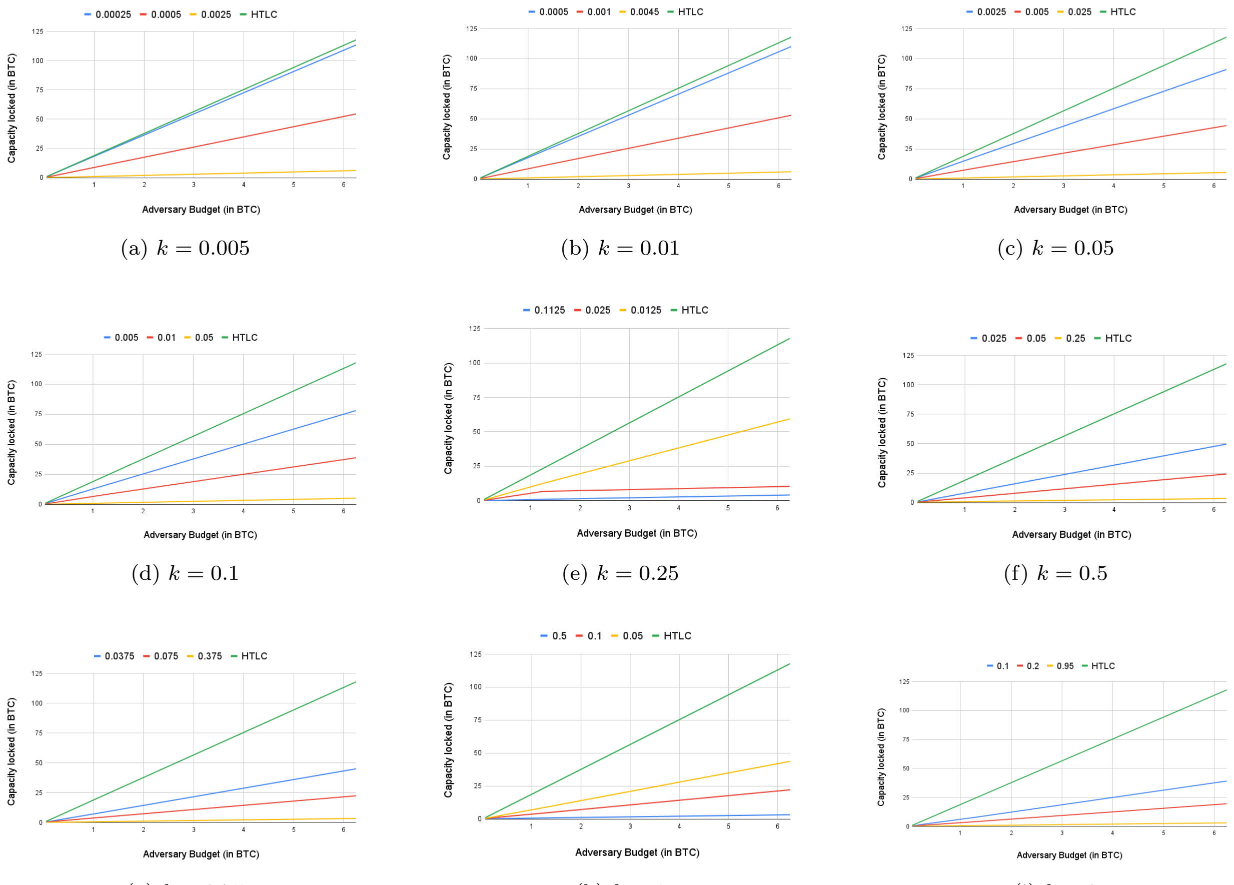
- $HTLC - GP^{\zeta}$: The observation for percentage loss in capacity is tabulated in Table 2 and the corresponding plot is shown in Fig.9(a)-(i). When $k$ is varied between 0.005 and 2, $\gamma$ ranges between $10^{-7}$ to $10^{-3}$, the drop in capacity locked ranges between 18% to 46%. The drop in collateral locked is significant for lower value of $\gamma$ and the difference reduces for $\gamma > 10^{-5}$.

## *9.4. Discussion of Results*

- *Expected Payoff in* $\Gamma_{HTLC}$ *and* $\Gamma_{HTLC-GP}$:
  - *Transaction amount is varied*: We see that expected payoff of $U_{n-1}$ in $\Gamma_{HTLC-GP}$ remains positive for a higher value of $\theta$ compared $\Gamma_{HTLC}$. The reason being that in the first game, $U_n$ can choose not to respond, forcing $U_{n-1}$ to go on-chain and close the channel. Since the mining fee for closing the channel is quite high, the stakes are higher. Thus $U_{n-1}$ tends to stop forwarding payment for $\theta$ as low as 0.025. In the second game, $U_n$ will always resolve the payment just before the lock time elapses to avoid paying penalty. This prevents abrupt closure of the channel. It is observed that the cutoff value of $\theta$ is higher for transaction amount 150000 satoshis. This is because the capacity locked is higher when the transaction amount increases, hence the risk is higher.
  - *Rate of the arrival of the transaction is varied*: In $\Gamma_{HTLC}$, varying the rate of arrival of the transaction has no impact on the payoff of both $U_{n-1}$ and $U_n$ because mining fee of channel closure dominates the result. In $\Gamma_{HTLC-GP}$, the value of $\theta$ increases with an increase in the rate of arrival of transaction. The reason behind this is that the distribution is positively skewed for a lower arrival rate. As the rate increases, the Poisson distribution becomes more symmetric and less peaked.

- *HTLC-GP*: To decrease the amount of collateral locked, $\gamma$ has to be increased. But this will force the recipient to lock a substantial amount of coins as a cumulative penalty. This will decrease the success rate of transactions.

- $HTLC - GP^{\zeta}$: When $\gamma$ increases, percentage loss in capacity locked for $HTLC - GP$ increases as well. But this is at the cost of a high failure rate of transactions. In this protocol, we observe that the capacity locked drops substantially even for lower values of $\gamma$ when $k$ and $\zeta$ are adjusted to reduce the maximum path length. So one need not compromise on the success rate of transactions. The limit on the maximum



(a) $k = 0.005$ (b) $k = 0.01$ (c) $k = 0.05$

(d) $k = 0.1$ (e) $k = 0.25$ (f) $k = 0.5$

(g) $k = 0.75$ (h) $k = 1$ (i) $k = 2$

Figure 9: Capacity locked vs Adversary's Budget

timeout period is 2016 blocks, i.e., the maximum timeout period cannot exceed this value in a given path [22]. So a corrupted node will divide 2016 blocks by $\tilde{n}$ to get the value $D$. $\gamma^{\zeta,k}$ will decrease if $D$ increases. The penalty locked doesn't change much, hence the capacity locked will not differ.

For a fixed value of $k$, $\zeta$ can be increased, reducing the maximum path length available for routing. This will increase the cost of the attack. When the majority of participants in the network adhere to non-attacking behavior, then the compensation offered can be reduced, readjusting the path length. Hence, the parameters must be chosen accordingly.

## 10. Conclusion

In this paper, we perform a strategic analysis of griefing attacks in Lightning Network. The model considers two-player interaction in *HTLC*, where one party chooses its strategy based on its' belief of the other player's type. We have analyzed the effectiveness of payment protocol *HTLC-GP* that uses penalization of the corrupted node for countering the griefing attack. It is observed that the cost of attack increases with the introduction of the penalty. Even if the attacker resorts to cancellation of payment just before the contract's lock time elapses, the capacity locked is less compared to the amount locked in *HTLC*. However, *HTLC-GP* is found to be weakly effective in countering the attack as it is dependent on the rate of griefing-penalty. To further increase the cost of the attack, we introduce the concept of guaranteed minimum compensation for the affected parties, which allows us to control the maximum path length used for routing.

| $k$ | $\zeta$ | $\gamma^{\zeta,k}$ | Maximum Path Length | Ratio of capacity locked | |
|---|---|---|---|---|---|
| | | | | $\frac{HTLC-GP^{\zeta}}{HTLC}$ | $\frac{HTLC-GP}{HTLC}$ |
| 0.005 | 0.00025 | $2.4 \times 10^{-7}$ | 20 | 96.89% | 96.89% |
| | 0.0005 | $9.1 \times 10^{-7}$ | 10 | 46.3% | 89.86% |
| | 0.0025 | $1.4 \times 10^{-5}$ | 2 | 5.21% | 50.7% |
| 0.01 | 0.0005 | $4.7 \times 10^{-7}$ | 20 | 94% | 94% |
| | 0.001 | $1.8 \times 10^{-6}$ | 10 | 44.8% | 81.5% |
| | 0.005 | $2.8 \times 10^{-5}$ | 2 | 5.1% | 42% |
| 0.05 | 0.0025 | $2.4 \times 10^{-6}$ | 20 | 78% | 78% |
| | 0.005 | $9.1 \times 10^{-6}$ | 10 | 38.2% | 54% |
| | 0.025 | $1.6 \times 10^{-4}$ | 2 | 4.7%% | 33% |
| 0.1 | 0.005 | $4.8 \times 10^{-6}$ | 20 | 67.5% | 67.5% |
| | 0.01 | $1.8 \times 10^{-5}$ | 10 | 33.5% | 45.5% |
| | 0.05 | $3.3 \times 10^{-4}$ | 2 | 4.45% | 32.5% |
| 0.25 | 0.0125 | $1.2 \times 10^{-5}$ | 20 | 53% | 53% |
| | 0.025 | $4.5 \times 10^{-5}$ | 10 | 28% | 40% |
| | 0.1125 | $6.9 \times 10^{-4}$ | 2 | 4.2% | 32% |
| 0.5 | 0.025 | $2.4 \times 10^{-5}$ | 20 | 44% | 44% |
| | 0.05 | $9.1 \times 10^{-5}$ | 10 | 22.1% | 38.5% |
| | 0.2 | $1.1 \times 10^{-3}$ | 2 | 3.8% | 31.5% |
| 0.75 | 0.0375 | $3.6 \times 10^{-5}$ | 20 | 41% | 41% |
| | 0.075 | $1.36 \times 10^{-4}$ | 10 | 21.2% | 35.6% |
| | 0.3 | $1.7 \times 10^{-3}$ | 2 | 3.51% | 30.04% |
| 1 | 0.05 | $4.8 \times 10^{-5}$ | 20 | 38% | 38% |
| | 0.1 | $1.8 \times 10^{-4}$ | 10 | 20% | 34% |
| | 0.5 | $3.3 \times 10^{-3}$ | 2 | 3.4% | 29.98% |
| 2 | 0.1 | $10^{-4}$ | 20 | 35% | 35% |
| | 0.2 | $3.6 \times 10^{-4}$ | 10 | 18% | 32% |
| | 0.95 | $6.1 \times 10^{-3}$ | 2 | 3.34% | 29.01% |

Table 2: Capacity Locked when $k$ and $\zeta$ is varied

We discuss a modified payment protocol $HTLC - GP^{\zeta}$ and our experimental results show that the former is more effective than *HTLC-GP* in the disincentivizing griefing attack.

As a part of our future work, we want to propose a fair compensation protocol considering different routing nodes have different estimates of loss suffered upon being subjected to griefing attack. We would like to study the attack when the network has both Byzantine and rational participants and analyze the effectiveness of the countermeasure in the new model.

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