

Elmo: Recursive Virtual Payment Channels for Bitcoin

Anonymised Submission

No Institute Given

Abstract. A dominant approach towards the solution of the scalability problem in blockchain systems has been the development of layer 2 protocols and specifically payment channel networks (PCNs) such as the Lightning Network (LN) over Bitcoin. Routing payments over LN requires the coordination of all path intermediaries in a multi-hop round trip that encumbers the layer 2 solution both in terms of responsiveness as well as privacy. The issue is resolved by “virtual channel” protocols that, capitalizing on a suitable off-chain setup operation, enable the two endpoints to engage as if they had a direct payment channel between them. Once the channel is unneeded, it can be optimistically closed in an off-chain fashion.

Apart from communication efficiency, virtual channel constructions have three natural desiderata. A virtual channel constructor is *recursive* if it can also be applied on pre-existing virtual channels, *variadic* if it can be applied on any number of pre-existing channels and *symmetric* if it encumbers in an egalitarian fashion all channel participants both in optimistic and pessimistic execution paths. We put forth the first Bitcoin-suitable recursive variadic virtual channel construction. Furthermore our virtual channel constructor is symmetric and offers optimal round complexity for payments, optimistic closing and unilateral closing. We express and prove the security of our construction in the universal composition setting.

1 Introduction

The popularity of blockchain protocols in recent years has stretched their performance exposing a number of scalability considerations. In particular, Bitcoin and related blockchain protocols exhibit very high latency (e.g. Bitcoin has a latency of 1h [47]) and a very low throughput (e.g., Bitcoin can handle at most 7 transactions per second [16]), both significant shortcomings that jeopardize wider use and adoption and are to a certain extent inherent [16]. To address these considerations a prominent approach is to optimistically handle payments via a “Payment Channel Network” (PCN) (see, e.g., [29] for a survey). Payments over a PCN happen *off-chain*, i.e. without adding any transactions to the underlying blockchain. They only use the blockchain as an arbiter in case of dispute.

The key primitive of PCN protocols is a payment channel. Two parties initiate the channel by locking some funds on-chain and subsequently exchange

direct messages to update the state of the channel. The key feature is that state updates are not posted on-chain and hence they remain unencumbered by the performance limitations of the underlying blockchain protocol. Given this primitive, multiple overlapping payment channels can be combined and form the PCN.

Closing a channel is an operation that involves posting the state of the channel on-chain. Closing should be efficient, i.e. needing $O(1)$ on-chain transactions, independent of the number of payments that have occurred off-chain. It is also essential that any party can unilaterally close a channel as otherwise a malicious counterparty (i.e. the other channel participant) could prevent an honest party from accessing their funds. This functionality however raises an important design consideration: how to prevent malicious parties from posting old states of the channel. Addressing this issue can be done with some suitable use of transaction “timelocks”, a feature that prevents a transaction or a specific script from being processed on-chain prior to a specific time (measured in block height). For instance, diminishing transaction timelocks facilitated the Duplex Micropayment Channels (DMC) [20] at the expense of bounding the overall lifetime of a channel. Using script timelocks, the Lightning Network (LN) [49] provided a better solution that enabled channels staying open for an arbitrary duration: the key idea was to duplicate the state of the channel between the two counterparties, say Alice and Bob, and facilitate a punishment mechanism that can be triggered by Bob whenever Alice posts an old state update and vice-versa. The script timelocking is essential to allow an honest counterparty some time to act.

Interconnecting channels in LN enables any two parties to transmit funds to each other as long as they can find a route of payment channels that connects them. The downside of this mechanism is that it requires the direct involvement of all the parties along the path for each payment. Instead, “virtual payment channels”, suggest the more attractive approach of putting a one-time off-chain initialization step to set up a virtual payment channel, which subsequently can be used for direct payments with complexity—in the optimistic case— independent of the length of the path. When the virtual channel has exhausted its usefulness, it can be closed off-chain if involved parties cooperate. Such a protocol can be very attractive for parties that need to send money to each other often. Initial constructions for virtual channels essentially capitalized on the extended functionality of Ethereum, e.g., Perun [23] and GSCN [25], while more recent work [5] brought them closer to Bitcoin-compatibility (by leveraging adaptor signatures [4]).

A virtual channel constructor can be thought of as an *operator* over the underlying primitive of a state channel. We can identify three natural desiderata for this operator.

- Recursive. A recursive virtual channel constructor can operate over channels that themselves could be the results of previous applications of the operator. This is important in the context of PCNs since it allows building virtual channels on top of pre-existing virtual channels, allowing the channel structure to evolve dynamically.

- Variadic. A variadic virtual channel constructor can virtualize any number of input state channels directly, i.e. without leveraging recursion. This is important in the context of PCNs since it enables applying the operator to build virtual channels of arbitrary length, without the undue overhead of opening, managing and closing multiple virtual channels only to use the one at the “top” of the recursion.
- Symmetric. A symmetric virtual channel constructor offers setup and closing operations that are symmetric in terms of cost between the two “endpoints” or the “intermediaries” (but not a mix of both) for the optimistic and pessimistic execution paths. This is important in the context of PCNs since it ensures that no party is worse-off or better-off after an application of the operator in terms of accessing the basic functionality of the channel.

Endpoints are the two parties that share the virtual channel, intermediaries are the parties that take part in any of underlying channels.

We note that recursiveness, while identified already as an important design property (e.g., see [25]), has not been achieved in the context of Bitcoin-compatible channels (it was achieved only for DMC-like fixed lifetime channels in [31] and left as an open question for LN-type channels in [5]). The reason behind this are the severe limitations imposed to the design by the scripting language of Bitcoin-compatible systems. With respect to the other two properties, observe that successive applications of a recursive *binary* virtual channel operator to make it variadic will break symmetry (since the sequence of operator applications will impact the participants’ functions with respect to the resulting channel). This is of particular concern since most previous virtual channel constructors proposed are binary, c.f. [25,5,31].

Our Contributions. We present the first Bitcoin-suitable recursive virtual channel constructor that supports channels with an indefinite lifetime. In addition, our constructor, Elmo (named after St. Elmo’s fire), is variadic and symmetric. In our constructor, both optimistic and pessimistic execution paths are optimal in terms of round complexity: issuing payments between the two endpoints requires just three messages of size independent of the length of the channel, closing the channel cooperatively requires at most three messages from each party while closing the channel unilaterally requires up to two on-chain transactions for any involved party (endpoint or intermediary) that can be submitted simultaneously, also independent of the channel’s length. Our construction is also compatible with the current version of any blockchain that supports Turing-complete smart contracts, such as Ethereum [54].

We achieve the above by leveraging a sophisticated virtual channel setup protocol which, on the one hand, enables endpoints to use an interface that is invariant between on-chain and off-chain (i.e. virtual) channels, while on the other, parties can securely close the channel cooperatively off-chain, or instead opt for unilateral on-chain closing, following any arbitrary activation sequence. The latter is achieved by making it feasible for anyone to become an initiator towards closing the channel, while subsequent respondents, following the activa-

tion sequence, can choose the right action to successfully complete the closure process by posting a single transaction each.

We formally prove the security of the constructor protocol in the Universally Composable security (UC) [13] setting; our ideal functionality is global, according to the definition of [9]. The construction relies on the ANYPREVOUT signature type (slated for inclusion in the next Bitcoin update), which does not sign the hash of the transaction it spends, therefore allowing for a single pre-signed transaction to spend any output with a suitable script. We conjecture that, if ANYPREVOUT is unavailable, no efficient virtual channel constructor protocol over Bitcoin can be built. More specifically, if any such protocol (i) offers an efficient closing operation (i.e. with $O(1)$ on-chain transactions) and (ii) has parties store the channel state as transactions and signatures in their local storage, then each party will need exponentially large space in the number of intermediaries. Note that the second protocol requirement is natural, since, to our knowledge, all trustless layer 2 protocols over Bitcoin require all implicated protocol parties to actively sign off every state transition and locally store the relevant transactions and signatures of their counterparties, thus ensuring their ability to unilaterally exit later.

Related work The first proposal for PCNs was due to [53] which only enabled unidirectional payment channels. As mentioned previously, DMCs [20] with their decrementing timelocks have the shortcoming of limited channel lifetime. This was ameliorated by LN [49] which has become the dominant paradigm for designing PCNs for Bitcoin-compatible systems. LN is currently implemented and operational for Bitcoin. It has also been adapted for Ethereum [54], where it is known as the Raiden Network [1].

A number of attacks have been identified against LN. The wormhole attack [44] against LN allows colluding parties in a multi-hop payment to steal the fees of the intermediaries between them and Flood & Loot attacks [30] analyses the feasibility of an attack in which too many channels are forced to close in a short amount of time, reducing the blockchain liveness and enabling a malicious party to steal off-chain funds.

To the best of our knowledge, no formal treatment of the privacy of LN exists. Nevertheless, it intuitively improves upon the privacy of on-chain Bitcoin transactions, as LN payments do not leave a permanent record: only intermediaries of each payment are informed. It can be argued that Elmo further improves privacy, as individual payments are completely hidden from the intermediaries of a virtual channel.

Payment routing [52,50,37] is another research area that aims to improve the network efficiency without sacrificing privacy. Actively rebalancing channels [33] can further increase network efficiency by preventing routes from becoming unavailable due to lack of well-balanced funds.

An alternative payment channel construction that aspires to be the successor of Lightning is eltoo [18]. It has a conceptually simpler construction, smaller on-chain footprint and a more forgiving attitude towards submitting an old channel state than Lightning, but it needs the ANYPREVOUT sighash flag to be added to

Bitcoin. Bolt [28] constructs privacy-preserving payment channels enabling both direct payments and payments with a single untrusted intermediary. Sprites [46] leverages the scripting language of Ethereum to decrease the time collateral is locked up compared to Lightning.

State channels are a generalisation of payment channels, which enable off-chain execution of any smart contract supported by the underlying blockchain, not just payments. Generalized Bitcoin-Compatible Channels [4] enable the creation of state channels on Bitcoin, extending channel functionality from simple payments to arbitrary Bitcoin scripts. State channels can also be extended to more than two parties [39,22].

Perun [23] and GSCN [25] exploit the Turing-complete scripting language of Ethereum to provide virtual state channels, i.e. state channels that can open without an on-chain transaction. Similar features are provided by Celer [21]. Hydra [14] provides state channels for the Cardano [15] blockchain which combines a UTXO type of model with general purpose smart contract functionality that are also isomorphic, i.e. Hydra channels can accommodate any script that is compatible with the underlying blockchain.

BDW [12] shows how pairwise channels over Bitcoin can be funded with no on-chain transactions by allowing parties to form groups that can pool their funds together off-chain and then use those funds to open channels. ACMU [26] allows for multi-path atomic payments with reduced collateral, enabling new applications such as crowdfunding conditional on reaching a funding target.

TEE-based [56] solutions [40,41,38,37] improve the throughput and efficiency of PCNs by an order of magnitude or more, at the cost of having to trust TEEs. Brick [7] uses a partially trusted committee to extend PCNs to fully asynchronous networks.

Solutions alternative to PCNs include sidechains (e.g., [8,27,35]), non-custodial chains (e.g., [48,36,24,2]), and partially centralised payment networks that entirely avoid using a blockchain [3,45,43,51].

Last but not least, a number of works propose virtual channel constructions for Bitcoin. Lightweight Virtual Payment Channels [31] enables a virtual channel to be opened on top of two preexisting channels and uses a technique similar to DMC, unfortunately inheriting the fixed lifetime limitation. Let “simple channels” be those built directly on-chain, i.e. channels that are not virtual. Bitcoin-Compatible Virtual Channels [5] also enables virtual channels on top of two preexisting simple channels and offers two protocols, the first of which guarantees that the channel will stay off-chain for an agreed period, while the second allows the single intermediary to turn the virtual into a simple channel. This strategy has the shortcoming that even if it is made recursive (a direction left open in [5]) after k applications of the constructor the virtual channel participant will have to publish on-chain k transactions in order to close the channel if all intermediaries actively monitor the blockchain.

Furthermore, Donner [6] is the first work to achieve variadic virtual channels without the need for recursion nor features that are not yet available in Bitcoin. This is achieved by having the funder use funds that are external to

the “base channels” (i.e. the channels that the virtual channel is based on), so a party that has all its coins in channels cannot fund a Donner channel; additionally, we conjecture that using external coins precludes variadic virtual channel designs that are not encumbered with limited lifetime. Furthermore, due to its incentive structure, all of the base channels are forced to close if the virtual channel is closed. Donner also relies on placeholder outputs which, due to the minimum coins they need to carry to exceed Bitcoin’s “dust limit”, may skew the incentives of rational players and adds to the opportunity cost of maintaining a channel. Furthermore, its design complicates future iterations that lift its current restriction that only one of the two channel parties can fund the virtual channel. Donner is more efficient than Elmo in terms of storage, computation and communication complexity, and boasts a simpler design, but has less room for optimisations and is not recursive.

We refer the reader to Table 1 for a comparison of the features and limitations of virtual channel protocols, including the one put forth in the current work.

Table 1. Features & requirements comparison of virtual channel protocols

	Unlimited lifetime	Recursive	Variadic	Script requirements
LVPC [31]	✗	● ^a	✗	Bitcoin
BCVC [5]	✓	✗	✗	Bitcoin
Perun [23]	✓	✗	✗	Ethereum
GSCN [25]	✓	✓	✗	Ethereum
Donner [6]	✗	✗	✓	Bitcoin
this work	✓	✓	✓	Bitcoin + ANYPREVOUT

^a lacks security analysis

2 Protocol Description

Conceptually, Elmo is split into four main actions: channel opening, payments, cooperative closing and unilateral closing. A channel (P_1, P_n) between parties P_1 and P_n may be opened directly on-chain, in which case the two parties follow an opening procedure similar to that of LN; such a channel is called “simple”. Otherwise it can be opened on top of a path of preexisting “base” channels $(P_1, P_2), (P_2, P_3), \dots, (P_{n-2}, P_{n-1}), (P_{n-1}, P_n)$, in which case (P_1, P_n) is a “virtual” channel (each base channel may itself be simple or virtual). For a virtual channel, all parties P_i on the path follow our novel protocol, setting aside funds in their channels as collateral for the new virtual channel that is being opened; this is done by creating so-called “virtual” transactions that essentially tie the spending of two adjacent base channels into a single atomic action. Once all intermediaries are done, P_1 and P_n finally create (and keep off-chain) their initial “commitment” transaction, following a logic similar to Lightning; their channel is now open.

A payment over an established channel follows a procedure heavily inspired by LN, but without the use of HTLCs. To be completed, a payment needs three messages to be exchanged by the two parties.

A virtual channel can be optimistically closed completely off-chain. Put simply, the parties that control the base channels revoke their virtual transactions and the related commitment transactions, effectively peeling one layer of virtualisation. Balances are redistributed so that intermediaries “break even”, while P_1 and P_n get their rightful coins as reflected in the last state of their virtual channel.

Finally, the unilateral closing procedure of a channel C does not need cooperation and consists of signing and publishing a number of transactions on-chain. As we will discuss later, the exact transactions that a party will publish vary depending on the actions of the parties controlling the channels that form the base of C and the channels that are based on C .

In a nutshell, a virtual channel is built on top of two or more “base” channels, which, due to the recursive property, may themselves be simple or virtual. The parties that control the base channels are called “base parties”. The fact that more than two base channels can be used by a single virtual channel is ensured by the variadic property.

In more detail, to open a channel (c.f. Figure 31) the two counterparties (a.k.a. “endpoints”) first create new keypairs and exchange the resulting public keys (2 messages), then prepare the underlying base channels if the new channel is virtual ($12 \cdot (n-1)$ total messages, i.e. 6 outgoing messages per endpoint and 12 outgoing messages per intermediary, for $n-2$ intermediaries), next they exchange signatures for their respective initial commitment transactions (2 messages) and lastly, if the channel is to be opened directly on-chain, the “funder” signs and publishes the “funding” transaction to the ledger. As we alluded to earlier, a channel with its funding transaction on-chain is called “simple”. A channel is either simple or virtual, not both. We here note that like LN, only one of the two parties, the funder, provides coins for a new channel. This limitation simplifies the execution model and the analysis, but can be lifted at the cost of additional protocol complexity.

Let us now introduce some notation used in figures with transactions. Reflecting the UTXO model, each transaction is represented by a circular, named node with one incoming edge per input and one outgoing edge per output. Each output can be connected with at most one input of another transaction; cycles are not allowed. Above an input or an output edge we note the number of coins it carries. In some figures the coins are omitted. Below an input we place the data carried and below an output its spending conditions (a.k.a script). For a connected input-output pair, we omit the data carried by the input. σ_K is a signature on the transaction by sk_K ; in all cases, signatures are carried by inputs. An output marked with pk_K needs a signature by sk_K to be spent. $m/\{pk_1, \dots, pk_n\}$ is an m -of- n multisig ($m \leq n$) that needs signatures from m distinct keys among sk_1, \dots, sk_n . If k is a spending condition, then $k + t$ is the same spending condition but with a relative timelock of t . Spending conditions

or data can be combined with logical “AND” (\wedge) and “OR” (\vee), so an output $a \vee b$ can be spent either by matching the condition a or the condition b , and an input $\sigma_a \wedge \sigma_b$ carries signatures from sk_a and sk_b . Note that all signatures for all multisig outputs make use of the ANYPREVOUT hash type.

2.1 Simple Channels

In a similar vein to earlier UTXO-based PCN proposals, having an open channel essentially means having very specific keys, transactions and signatures at hand, as well as checking the ledger periodically and being ready to take action if misbehaviour is detected. Let us first consider a simple channel that has been established between *Alice* and *Bob* where the former owns c_A and the latter c_B coins. There are three sets of transactions at play: A “funding” transaction that is put on-chain, “commitment” transactions that are stored off-chain and spend the funding output on channel closure and off-chain “revocation” transactions that spend commitment outputs in case of misbehaviour (c.f. Figure 1).

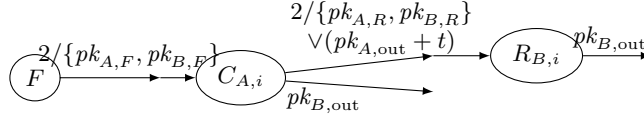


Fig. 1. Funding, commitment and revocation transactions

In particular, there is a single on-chain funding transaction that spends $c_A + c_B$ coins (originally belonging to the funder), with a single output that is encumbered with a $2/{pk_{A,F}, pk_{B,F}}$ multisig and carries $c_A + c_B$ coins.

Next, there are two commitment transactions, one for each party, each of which can spend the funding tx and produce two outputs with c_A and c_B coins each. The two txs differ in the outputs’ spending conditions: The c_A output in *Alice*’s commitment tx can be spent either by *Alice* after it has been on-chain for a pre-agreed period (i.e. it is encumbered with a “timelock”), or by a “revocation” transaction (discussed below) via a 2-of-2 multisig between the counterparties, whereas the c_B output can be spent only by *Bob* without a timelock. *Bob*’s commitment tx is symmetric: the c_A output can be spent only by *Alice* without timelock and the c_B output can be spent either by *Bob* after the timelock expiration or by a revocation tx. When a new pair of commitment txs are created (either during channel opening or on each update) *Alice* signs *Bob*’s commitment tx and sends him the signature (and vice-versa), therefore *Alice* can later unilaterally sign and publish her commitment tx but not *Bob*’s (and vice-versa).

Last, there are $2m$ revocation transactions, where m is the total number of updates of the channel. The j th revocation tx held by an endpoint spends

the output carrying the counterparty’s funds in the counterparty’s j th commitment tx. It has a single output spendable immediately by the aforementioned endpoint. Each endpoint stores m revocation txs, one for each superseded commitment tx. This creates a disincentive for an endpoint to cheat by using any other commitment transaction than its most recent one to close the channel: the timelock on the commitment output permits its counterparty to use the corresponding revocation transaction and thus claim the cheater’s funds. Endpoints do not have a revocation tx for the last commitment transaction, therefore these can be safely published. For a channel update to be completed, the endpoints must exchange the signatures for the revocation txs that spend the commitment txs that just became obsolete.

Observe that the above logic is essentially a simplification of LN.

2.2 Virtual Channels

In order to gain intuition on how virtual channels work, consider $n - 1$ simple channels between n honest parties as before. P_1 , the funder, and P_n , the fundee, want to open a virtual channel over these base channels. Before opening the virtual, each base channel is entirely independent, having different unique keys, separate on-chain funding outputs, a possibly different balance and number of updates. After the n parties follow our novel virtual channel opening protocol, they will all hold off-chain a number of new, “virtual” transactions that spend their respective funding transactions and can themselves be spent by new commitment transactions in a manner that ensures fair funds allocation for all honest parties.

In particular, apart from the transactions of simple channels (i.e. commitment and revocation txs), each of the two endpoints also has an “initiator” transaction that spends the funding output of its only base channel and produces two outputs: one new funding output for the base channel and one “virtual” output (c.f. Figures 2, 52). If the initiator transaction ends up on-chain honestly, the latter output carries coins that will directly or indirectly fund the funding output of the virtual channel. This virtual funding output can in turn be spent by a commitment transaction that is negotiated and updated with direct communication between the two endpoints in exactly the same manner as the payments of simple channels.

Intermediaries on the other hand store three sets of virtual transactions (Figure 51): “initiator” (Figure 3), “extend-interval” (Figure 4) and “merge-intervals” (Figure 5). Each intermediary has one initiator tx, which spends the party’s two funding outputs and produces four: one funding output for each base channel, one output that directly pays the intermediary coins equal to the total value in the virtual channel, and one “virtual output”, which carries coins that can potentially fund the virtual channel. If both funding outputs are still unspent, publishing its initiator tx is the only way for an honest intermediary to close either of its channels.

Furthermore, each intermediary has $O(n)$ extend-interval transactions. Being an intermediary, the party is involved in two base channels, each having its own

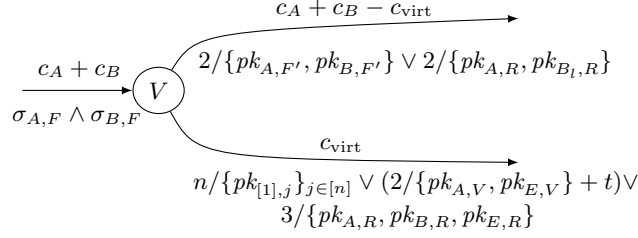


Fig. 2. $A - E$ virtual channel: A 's initiator transaction. Spends the funding output of the $A - B$ channel. Can be used if B has not published a virtual transaction yet.

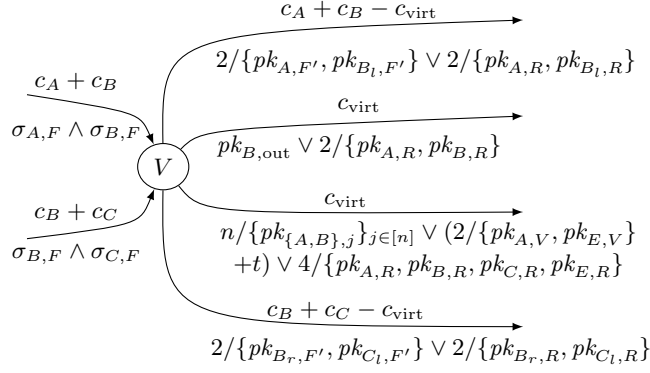


Fig. 3. $A - E$ virtual channel: B 's initiator transaction. Spends the funding outputs of the $A - B$ and $B - C$ channels. Can be used if neither A nor C have published a virtual transaction yet.

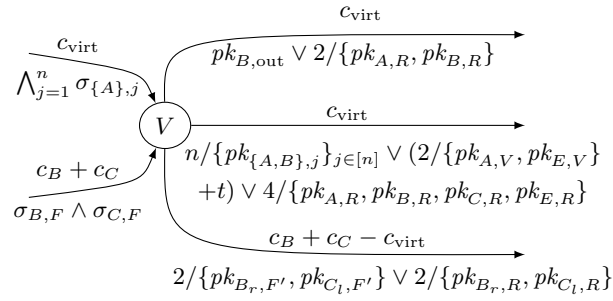


Fig. 4. $A - E$ virtual channel: One of B 's extend interval transactions. σ is the signature. Spends the virtual output of A 's initiator transaction and the funding output of the $B - C$ channel. Can be used if A has already published its initiator transaction and C has not published a virtual transaction yet.

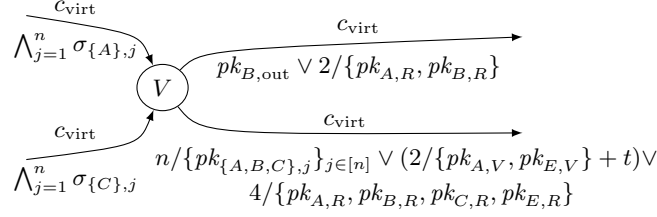


Fig. 5. *A - E* virtual channel: One of *B*'s merge intervals transactions. Spends the virtual outputs of *A*'s and *C*'s virtual transactions. Can be used if both *A* and *C* have already published their initiator transactions. Notice that the interval of *C*'s virtual output only contains *C*, which can only happen if *C* has published its initiator and not any other of its virtual transactions.

funding output. In case exactly one of these two outputs has been spent honestly and the other is still unspent, publishing an extend-interval transaction is the only way for the party to close the base channel corresponding to the unspent output and take its funds. Such a transaction consumes two outputs: the only available funding output and a suitable virtual output, as discussed below. An extend-interval tx has three outputs: A funding output replacing the one just spent, one output that directly pays the intermediary coins equal to the total value of the virtual channel, and one virtual output.

Last, each intermediary has $O(n^2)$ merge-intervals transactions. If both base channels' funding outputs of the party have been spent honestly, publishing a merge-intervals transaction is the only way for the party to close either base channel. Such a transaction consumes two suitable virtual outputs, as discussed below. It has two outputs: One that directly pays the intermediary coins equal to the total value of the virtual channel, and one virtual output.

Note that each output of a virtual transaction has a “revocation” spending method that needs a signature from every party that may end up owning the output coins: each funding output is signed by the two parties of the corresponding channel, each refund output is signed by the transaction owner and the party to the left (giving c_{virt} coins to the left party if the owner acts maliciously), whereas each virtual output is signed by the transaction owner, the right party and the two virtual channel parties. If the owner acts maliciously, c_{virt} are given to the right party. The virtual channel parties have to sign as well since this output may end up funding their channel – lack of such signatures would allow two colluding intermediaries to claim the virtual output for themselves.

To understand why this multitude of virtual transactions is needed, we now zoom out from the individual party and discuss the dynamic of unilateral closing as a whole. The first party P_i that wishes to close a base channel observes that its funding output(s) remain(s) unspent and publishes its initiator transaction. First, this allows P_i to use its commitment transaction to close the base channel. Second, in case P_i is an intermediary, it directly regains the coins it has locked

for the virtual channel. Third, it produces a virtual output that can only be consumed by P_{i-1} and P_{i+1} , the parties adjacent to P_i (if any) with specific extend-interval transactions. The virtual output of this extend-interval transaction can in turn be spent by specific extend-interval transactions of P_{i-2} or P_{i+2} that have not published a virtual transaction yet (if any) and so on for the next neighbours. The idea is that each party only needs to publish a single virtual transaction to “collapse” the virtual layer and each virtual output uniquely defines the continuous interval of parties that have already published a virtual transaction and only allows parties at the edges of this interval to extend it. This prevents malicious parties from indefinitely replacing a virtual output with a new one. As the name suggests, merge-intervals transactions are published by parties that are adjacent to two parties that have already published their virtual transactions and in effect joins the two intervals into one.

Each virtual output can also be used as the funding output for the virtual channel after a timelock, to protect from unresponsive parties blocking the virtual channel indefinitely. This in turn means that if an intermediary observes either of its funding outputs being spent, it has to publish its suitable virtual transaction before the timelock expires to avoid losing funds. What is more, all virtual outputs need the signature of all parties to be spent before the timelock (i.e. they have an n -of- n multisig) in order to prevent colluding parties from faking the intervals progression. To ensure that parties have an opportunity to react, the timelock of a virtual output is the maximum of the required timelocks of the intermediaries that can spend it. Let p be a global constant representing the maximum number of blocks a party is allowed to stay offline between activations without becoming negligent (the latter term is explained in detail later), and s the maximum number of blocks needed for an honest transaction to enter the blockchain after being published, as in Proposition 1 of Section E. The required timelock of a party is $p + s$ if its channel is simple, or $p + \sum_{j=2}^{n-1} (s - 1 + t_j)$ if the channel is virtual, where t_j is the required timelock of the base channel of the j th intermediary’s channel. The only exception are virtual outputs with an interval that includes all parties, which are just funding outputs for the virtual channel: an interval with all parties cannot be further extended, therefore one spending method and the timelock are dropped.

A typical extend-interval and merge-intervals transaction has to be able to spend different outputs, depending on the order other base parties publish their virtual transactions. For example, P_3 ’s extend-interval tx that extends the interval $\{P_1, P_2\}$ to $\{P_1, P_2, P_3\}$ must be able to spend both the virtual output of P_2 ’s initiator transaction and P_2 ’s extend-interval transaction which has spent P_1 ’s initiator transaction. The same issue is faced by commitment transactions of a virtual channel, as any virtual output can potentially be used as the funding output for the channel. In order for the received signatures for virtual and commitment txs to be valid for multiple previous outputs, the previously proposed **ANYPREVOUT** sighash flag [19] is needed to be added to Bitcoin. We conjecture that variadic recursive virtual channels with $O(1)$ on-chain and subexponential num-

ber of off-chain transactions of size $O(1)$ for each party cannot be constructed in Bitcoin without this flag.¹ We hope this work provides additional motivation for this flag to be included in the future.

Note also that the newly established virtual channel can itself act as a base for further virtual channels, as its funding output can be unilaterally put on-chain in a pre-agreed maximum number of blocks. This in turn means that, as we discussed above, a further virtual channel must take the delay of its virtual base channels into account to determine the timelocks needed for its own virtual outputs.

Let a single *channel round* be a series of messages starting from the funder and hop by hop reaching the fundee and back again. For the actual protocol that establishes a virtual channel 6 channel rounds are needed (c.f. Figure 27). The first communicates parties’ identities, their funding keys, revocation keys and their neighbours’ channel balances, the second creates new commitment transactions, the third communicates keys for virtual transactions (a.k.a. virtual keys), all parties’ coins and desired timelocks, the fourth and the fifth communicate signatures for the virtual transactions (signatures for virtual outputs and funding outputs respectively) and the sixth shares revocation signatures for the old channel states.

Cooperative closing is quite intuitive (c.f. Figures 44, 45, 46, 47 and 63). It can be initiated by any party, one and a half communication rounds are needed. The funder builds new commitment txs, which once again spend the funding outputs that the virtual txs spent before, just like prior to opening the virtual channel. The funder sends their signatures to the first intermediary; the latter signs and sends the same to the second intermediary and so on until the fundee. The fundee responds with its own commitment tx signatures, along with signatures revoking the previous commitment tx and virtual txs. This is repeated backwards until revocations reach the funder. Finally the funder sends its revocation to its neighbour and it to the next, until the revocations reach the fundee. The channel has now closed cooperatively.

As for the unilateral closing, let us now turn to an example in order to better grasp how our construction plays out on-chain in practice (Figure 6). Consider an established virtual channel on top of 4 preexisting simple base channels. Let A , B , C , D and E be the relevant parties, which control the (A, B) , (B, C) , (C, D) and (D, E) base channels, along with the (A, E) virtual channel. After carrying out some payments, A decides to unilaterally close the virtual channel. It therefore

¹ To see why, consider a virtual channel over $k + 1$ players who close the channel non-cooperatively via on-chain interaction. Assuming the $(k + 1)$ -th party goes last, the protocol should be able to accommodate any possible activation sequence for the first k parties. Consecutive pairs of parties $(i, i + 1)$ need to be reactive to each other’s posted transactions since they share a base channel. It follows that for each i we can assign either “L” or “R” signifying the directionality of reaction, resulting in a total of 2^{k-1} different sequences. Without ANYPREVOUT, the $(k + 1)$ -th party needs a different transaction to interact with the outcome of each sequence, hence blowing up its local storage. The formalization of this argument is outside the scope of the present work.

publishes its initiator transaction, thus consuming the funding output of (A, B) and producing (among others) a virtual output with the interval $\{A\}$. B notices this before the timelock of the virtual output expires and publishes its extend-interval transaction that consumes the aforementioned virtual output and the funding output of (B, C) , producing a virtual output with the interval $\{A, B\}$. C in turn publishes the corresponding extend-interval transaction, consuming the virtual output of B and the funding output of (C, D) while producing a virtual output with the interval $\{A, B, C\}$. Finally D publishes the last extend-interval transaction, thus producing an interval with all players. Instead of a virtual output, it produces the funding output for the virtual channel (A, E) . Now A can spend this funding output with its latest commitment transaction. Note that if any of B , C or D does not act within the timelock prescribed in their consumed virtual output, then A or E can spend the virtual output with their latest commitment transaction, thus eventually A can close its virtual channel in all cases.

3 Model

3.1 $\mathcal{G}_{\text{Ledger}}$ Functionality

In this work we embrace the Universal Composition (UC) framework [13] together with its global subroutines extension, UCGS [9], to model parties, network interactions, adversarial influence and corruptions, as well as formalise and prove security. We choose to model the Bitcoin ledger with the $\mathcal{G}_{\text{Ledger}}$ functionality as defined in [11] and further refined in [10]. $\mathcal{G}_{\text{Ledger}}$ formalizes an ideal data structure that is distributed and append-only, akin to a blockchain. Participants can read from $\mathcal{G}_{\text{Ledger}}$, which returns an ordered list of transactions. Additionally a party can submit a new transaction which, if valid, will eventually be added to the ledger when the adversary decides, but necessarily within a predefined time window. This property is named liveness. Once a transaction becomes part of the ledger, it then becomes visible to all parties at the discretion of the adversary, but necessarily within another predefined time window, and it cannot be reordered or removed. This is named persistence.

Moreover, $\mathcal{G}_{\text{Ledger}}$ needs the $\mathcal{G}_{\text{Clock}}$ functionality [32], which models the notion of time. Any $\mathcal{G}_{\text{Clock}}$ participant can request to read the current time (which is initially 0) and inform $\mathcal{G}_{\text{Clock}}$ that her round is over. $\mathcal{G}_{\text{Clock}}$ increments the time by one once all parties have declared the end of their round. We further note that both $\mathcal{G}_{\text{Ledger}}$ and $\mathcal{G}_{\text{Clock}}$ are global functionalities [9] and therefore can be accessed directly by the environment.

3.2 Modelling time

The protocol and functionality defined in this work do not use $\mathcal{G}_{\text{Clock}}$ directly. Indeed, the only notion of time in our work is provided by the blockchain height, as reported by $\mathcal{G}_{\text{Ledger}}$. We therefore omit it in the statement of our lemmas

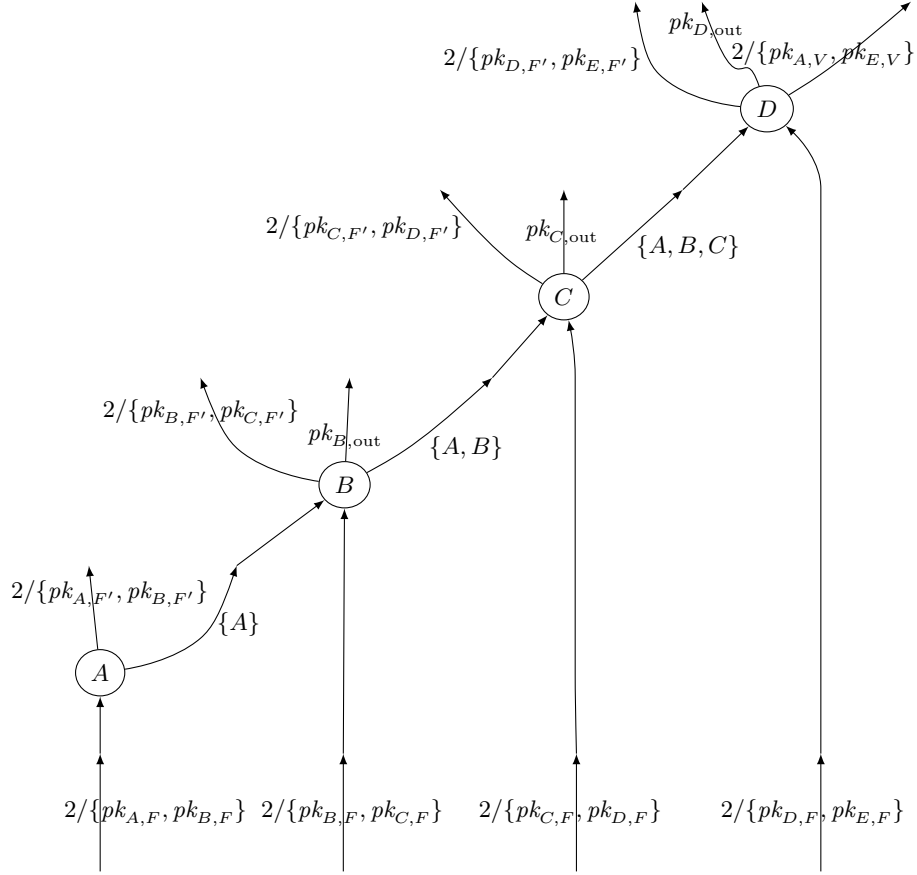


Fig. 6. 4 simple channels supporting a virtual. *A* initiates the closing procedure and no party is negligent. Virtual outputs are marked with their interval.

and theorems for simplicity of notation; it should normally appear as a hybrid together with $\mathcal{G}_{\text{Ledger}}$.

Our protocol is fully asynchronous, i.e., the adversary can delay any network message arbitrarily long. The protocol is robust against such delays, as an honest party can unilaterally prevent loss of funds even if some of its incoming and outgoing network messages are dropped by \mathcal{A} , as long as the party has input-output communication with the ledger. We also note that, following the conventions of single-threaded UC execution model, the duration of local computation is not taken into account in any way (as long as it does not exceed its polynomial bound).

4 Protocol Pseudocode

We here present a simplified version of the protocol in pseudocode form. We omit complications imposed by UC. We refer the reader to Appendix D for the complete protocol and to Appendix C for an in-depth description of the protocol in prose.

Process $\Pi_{\text{Chan}} - \text{self is } P$

- Before handling each message:
 - if** we have not been activated since more than p blocks **then**
 - Mark ourselves as negligent // no balance security guarantees anymore
 - end if**
- Initialisation:
 - Receive $pk_{P,\text{out}}$ from \mathcal{E} // all outputs owned by P pay $pk_{P,\text{out}}$
 - Generate own keypair
 - Wait for \mathcal{E} to give own keypair some starting coins
- Opening:
 - Generate funding and revocation keypairs
 - Exchange funding, revocation and out public keys with counterparty
 - if** opening virtual (off-chain) channel **then**
 - Ask our host channel to prepare, passing them our funding keys // c.f. next bullet, “Hosting a virtual channel”
 - Get t_P from host // timelock to ensure our balance security
 - end if**
 - Exchange and verify signatures on commitment transactions with counterparty
 - if** opening simple (on-chain) channel **then**
 - Prepare and submit funding transaction to ledger and wait for its inclusion // only one party funds the channel, so the funding transaction needs only the funder’s signature
 - $t_P \leftarrow s + p$ // timelock to ensure balance security for simple channels
 - end if**
- Hosting a virtual channel of c_{virt} coins:
 - Ensure we have enough coins to host such a virtual channel

Generate one new funding keypair, $O(n^2)$ virtual keypairs ($O(n)$ per hop) and one virtual revocation keypair // all keypairs are generated normally, using `KEYGEN()`
 Exchange generated public keys among all base channel parties
 Generate and sign new commitment transactions with our counterparties. The new funding keys and the latest revocation keys are used and the balance of the party “closer” to the funder is reduced by c_{virt} // 1 counterparty if we are endpoint, 2 counterparties if we are intermediary
 Exchange signatures with counterparties and verify them
 Generate and sign all $O(n^3)$ virtual transactions // one signature for each virtual input – each virtual input needs one signature from each party. Only “extend-interval” and “merge-intervals” transactions need these signatures
 Exchange all signatures among all base channel parties and verify that all our virtual transactions have fully signed virtual inputs
 Exchange with counterparties and verify signatures for the funding inputs of our virtual transactions // only “initiator” and “extend-interval” transactions need these signatures
 Exchange with counterparties and verify signatures for the revocation transactions of the previous channel state
if P is intermediary **then**
 $t_P \leftarrow \max\{t \text{ of left channel}, t \text{ of right channel}\}$
else // P is endpoint
 $t_P \leftarrow p + \sum_{j=2}^{n-1} (s - 1 + t_j)$ // worst case delay is if counterparty uses initiator tx and every intermediary uses its extend-interval tx sequentially – the maximum possible delay is $O(\text{sum of intermediaries' delays})$
end if
 – Reacting if counterparty publishes virtual transaction:
 if both our counterparties have published a virtual transaction **then**
 Publish our merge-intervals transaction that has an interval equal to the union of the intervals of the two virtual transactions plus ourselves
 else // exactly one of our counterparties has published a virtual transaction
 Publish our extend-interval transaction that has an interval equal to the interval of the virtual transaction plus ourselves
 end if
 – Paying x coins:
 Ensure we have enough coins to pay
 if we host a virtual channel **then**
 Ensure balance after payment will not allow griefing attack // c.f. Subsubsection C.3
 end if
 Generate and sign new commitment transactions, with x coins less for the payer and x coins more for the payee and using the latest revocation keys
 Exchange and verify signatures
 Sign revocation transactions that correspond to the old commitment transactions
 Generate next revocation keypairs

```

    Exchange and verify commitment signatures and revocation public keys
  - Unilaterally closing:
    Publish all initiator transactions that are needed to put our funding output
    on the ledger
    Publish our latest commitment transaction to the ledger
  - Cooperatively closing:
    // Only a virtual channel which does not host any further virtual channel
    may close cooperatively
    Both endpoints sign and broadcast the final virtual channel balance  $(c_1, c_2)$ 
    Every party verifies both signatures, ensures that the two opinions agree and
    that the balance sum is equal to  $c_{\text{virt}}$ 
    Generate and sign new commitment transactions with:
    • the most recent old funding keys (the ones used before hosting the virtual
      channel)
    • the new revocation keys
    •  $c_1$  additional coins for the party closest to the virtual channel funder and
       $c_2$  for the counterparty
    Generate new revocation keypairs
    Exchange and verify signatures and revocation public keys
    Generate and sign revocation transactions for both the old virtual
    transactions (with the virtual revocation keys) and the old commitment
    transactions (with the normal revocation keys)
    Exchange and verify signatures // if a party publishes a revoked virtual
    transaction, its various outputs can be spent by revocation transactions so
    that its (1 or 2) counterparties can claim all base channel funds
  - Punishing malicious counterparties:
    // Executed at least every  $p$  blocks
    if the ledger contains an old commitment transaction then
      Sign and publish the corresponding revocation transaction
    end if
    if the ledger contains an old virtual transaction then
      Sign and publish the corresponding revocation transaction(s)
    end if

```

Fig. 7. High level pseudocode of the Elmo protocol

5 Security

The first step to formally arguing about the security of Elmo is to clearly delineate the exact security guarantees it provides. To that end, we first prove two similar claims regarding the conservation of funds in the real and ideal world, Lemmas 1 and 2 respectively. Informally, the first establishes that if an honest, non-negligent party was implicated in a channel on which a number of payments

took place and has now been unilaterally closed, then the party will have at least the expected funds on-chain.

Lemma 1 (Real world balance security (informal)). *Consider a real world execution with $P \in \{\text{Alice}, \text{Bob}\}$ honest LN ITI. Assume that all of the following are true:*

- P is not negligent,
- P successfully opened the channel, with initial balance c ($c = 0$ if P is a fundee)
- P is the host of n channels, where the i -th channel is funded with f_i coins,
- P has cooperatively closed k channels, where the i -th channel transferred r_i coins from the hosted virtual channel to P ,
- P has successfully sent m payments, where the i -th payment involved d_i coins,
- P has successfully received l payments, where the i -th payment involved c_i coins.

If P unilaterally closes its channel, eventually its view of $\mathcal{G}_{\text{Ledger}}$ will contain h outputs spendable only by P or another kindred party, each of value c_i , such that

$$\sum_{i=1}^h c_i \geq c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^k r_i . \quad (1)$$

The formal statement, Lemma 4, is deferred to the Appendix.

The second lemma states that for an ideal party in a similar situation, the balance that $\mathcal{G}_{\text{Chan}}$ has stored for it is at least equal to the expected funds.

Lemma 2 (Ideal world balance (informal)). *Consider an ideal world execution with functionality $\mathcal{G}_{\text{Chan}}$ and simulator \mathcal{S} . Let $P \in \{\text{Alice}, \text{Bob}\}$ one of the two parties of $\mathcal{G}_{\text{Chan}}$. Assume that all of the following are true:*

- P is not corrupted or negligent, nor any member of the transitive closure of its hosts has published a revocation transaction,
- P successfully opened the channel, with initial balance c ($c = 0$ if P is a fundee)
- P is the host of n channels, where the i -th channel is funded with f_i coins,
- P has cooperatively closed k channels, where the i -th channel transferred r_i coins from the hosted virtual channel to P ,
- P has successfully sent m payments, where the i -th payment involved d_i coins,
- P has successfully received l payments, where the i -th payment involved c_i coins.

Let balance_P be the balance that $\mathcal{G}_{\text{Chan}}$ stores internally for P . If the channel is closed (either unilaterally or cooperatively), then the following holds with overwhelming probability on the security parameter:

$$\text{balance}_P = c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^k r_i + \sum_{i=1}^k r_i . \quad (2)$$

The formal statement, Lemma 5, is deferred to the Appendix.

In both cases the expected funds are [initial balance - funds for hosted virtuals + funds returned from hosted virtuals - outbound payments + inbound payments]. Note that the funds for hosted virtuals only refer to those funds used by the funder of the virtual channel, not the rest of the base parties.

Both proofs follow all possible execution paths, keeping track of the resulting balance in each case and coming to the conclusion that balance is secure in all cases, except if signatures are forged.

It is important to note that in fact Π_{Chan} provides a stronger guarantee, namely that an honest, non-negligent party with an open channel can unilaterally close it and obtain the expected funds on-chain within a known number of blocks, given that \mathcal{E} sends the necessary “daemon” messages. This stronger guarantee is sufficient to make Elmo reliable enough for real-world applications. However a corresponding ideal world functionality with such guarantees would have to be aware of the specific transactions and signatures, therefore it would be essentially as complicated as the protocol, thus violating the spirit of the simulation-based security paradigm.

Subsequently we prove Lemma 3, which informally states that if an ideal party and all its kindred parties are honest, then $\mathcal{G}_{\text{Chan}}$ does not halt with overwhelming probability.

Lemma 3 (No halt). *In an ideal execution with $\mathcal{G}_{\text{Chan}}$ and \mathcal{S} , if the kindred parties of the honest parties of $\mathcal{G}_{\text{Chan}}$ are themselves honest, then the functionality halts with negligible probability in the security parameter (i.e. l. 21 of Fig. 12 is executed negligibly often).*

This is proven by first arguing that if the conditions of Lemma 5 for the ideal world hold, then the conditions of Lemma 4 also hold for the equivalent real world execution, therefore in this case $\mathcal{G}_{\text{Chan}}$ does not halt. We then argue that also in case the conditions of Lemma 5 do not hold, $\mathcal{G}_{\text{Chan}}$ may never halt as well, therefore concluding the proof. The formal proofs are deferred to Appendix F.

A salient observation regarding an instance s of Π_{Chan} is that, in order to open a virtual channel, it passes inputs to another Π_{Chan} instance s' that belongs to a different extended session. This means that s (and therefore Π_{Chan}) is not *subroutine respecting*, as defined in [13]. To address this issue, we first annotate Π_{Chan} with a numeric superscript, i.e. Π_{Chan}^n . Π_{Chan}^1 is always a simple (i.e. on-chain) channel. To achieve this, Π_{Chan} undergoes a modification under which it ignores all (OPEN, x , hops \neq “ledger”, ...) messages. Likewise we define $\mathcal{G}_{\text{Chan}}^1$ as a version of $\mathcal{G}_{\text{Chan}}$ that ignores (OPEN, x , hops \neq “ledger”, ...) messages. As for the rest of the superscripts, $\forall n \in \mathbb{N}^*$, Π_{Chan}^{n+1} is a virtual channel protocol Π_{Chan} of which the base channels have a maximum superscript n . It then holds that $\forall n \in \mathbb{N}^*$, Π_{Chan}^n is $(\mathcal{G}_{\text{Ledger}}, \Pi_{\text{Chan}}^1, \dots, \Pi_{\text{Chan}}^{n-1})$ -subroutine respecting, as defined in [9]. Likewise, $\mathcal{G}_{\text{Chan}}^{n+1}$ is a virtual channel functionality $\mathcal{G}_{\text{Chan}}$ of which the base channels have a maximum superscript n . It then holds that $\forall n \in \mathbb{N}^*$, $\mathcal{G}_{\text{Chan}}^n$ is $(\mathcal{G}_{\text{Ledger}}, \mathcal{G}_{\text{Chan}}^1, \dots, \mathcal{G}_{\text{Chan}}^{n-1})$ -subroutine respecting.

We now formulate and prove Theorem 1, which states that Π_{Chan}^1 UC-realises $\mathcal{G}_{\text{Chan}}^1$.

Theorem 1 (Simple Payment Channel Security). *The protocol Π_{Chan}^1 UC-realises $\mathcal{G}_{\text{Chan}}^1$ in the presence of a global functionality $\mathcal{G}_{\text{Ledger}}$ and assuming the security of the underlying digital signature:*

$$\forall \text{ PPT } \mathcal{A}, \exists \text{ PPT } \mathcal{S} : \forall \text{ PPT } \mathcal{E} \text{ it is } \text{EXEC}_{\Pi_{\text{Chan}}^1, \mathcal{A}, \mathcal{E}}^{\mathcal{G}_{\text{Ledger}}} \approx \text{EXEC}_{\mathcal{S}, \mathcal{E}}^{\mathcal{G}_{\text{Chan}}^1, \mathcal{G}_{\text{Ledger}}}$$

The corresponding proof stems from Lemma 3, the fact that $\mathcal{G}_{\text{Chan}}$ is a simple relay and that \mathcal{S} faithfully simulates Π_{Chan} .

Proof (Proof of Theorem 1). By inspection of Figures 8 and 22 we can deduce that for a particular \mathcal{E} , in the ideal world execution $\text{EXEC}_{\mathcal{S}, \mathcal{E}}^{\mathcal{G}_{\text{Chan}}^1, \mathcal{G}_{\text{Ledger}}}$, $\mathcal{S}_{\mathcal{A}}$ simulates internally the two Π_{Chan}^1 parties exactly as they would execute in $\text{EXEC}_{\Pi_{\text{Chan}}^1, \mathcal{A}, \mathcal{E}}^{\mathcal{G}_{\text{Ledger}}}$, the real world execution, in case $\mathcal{G}_{\text{Chan}}^1$ does not halt. Indeed, $\mathcal{G}_{\text{Chan}}^1$ only halts with negligible probability according to Lemma 3, therefore the two executions are computationally indistinguishable.

Lastly we prove that \forall integers $n \geq 2$, Π_{Chan}^n UC-realises $\mathcal{G}_{\text{Chan}}^n$ in the presence of $\mathcal{G}_{\text{Chan}}^1, \dots, \mathcal{G}_{\text{Chan}}^{n-1}$ (leveraging the relevant definition from [9]).

Theorem 2 (Recursive Virtual Payment Channel Security). $\forall n \in \mathbb{N}^* \setminus \{1\}$, *the protocol Π_{Chan}^n UC-realises $\mathcal{G}_{\text{Chan}}^n$ in the presence of $\mathcal{G}_{\text{Chan}}^1, \dots, \mathcal{G}_{\text{Chan}}^{n-1}$ and $\mathcal{G}_{\text{Ledger}}$, assuming the security of the underlying digital signature. Specifically,*

$$\forall n \in \mathbb{N}^* \setminus \{1\}, \forall \text{ PPT } \mathcal{A}, \exists \text{ PPT } \mathcal{S} : \forall \text{ PPT } \mathcal{E} \text{ it is } \text{EXEC}_{\Pi_{\text{Chan}}^n, \mathcal{A}, \mathcal{E}}^{\mathcal{G}_{\text{Ledger}}, \mathcal{G}_{\text{Chan}}^1, \dots, \mathcal{G}_{\text{Chan}}^{n-1}} \approx \text{EXEC}_{\mathcal{S}, \mathcal{E}}^{\mathcal{G}_{\text{Chan}}^n, \mathcal{G}_{\text{Ledger}}}$$

Proof (Proof of Theorem 2). The proof is exactly the same as that of Theorem 1, replacing superscripts 1 for n .

6 Efficiency Evaluation

We offer here a comparison of this work with LVPC [31], BCVC [5] and Donner [6] in terms of communication efficiency when opening and updating. We also compare the maximum on-chain cost for an endpoint to unilaterally close its virtual channel. Furthermore, we compare the worst-case on-chain cost for an intermediary to close its base channel. Note that, in order to only show the costs caused by supporting a virtual channel, we subtract the cost the intermediary would pay to close its channel if it was not supporting any virtual channel. Lastly, we compare the worst-case total on-chain cost, aggregated over all parties. On-chain cost is measured in terms of size² and number of transactions.

² For Table 4, transaction size is calculated in so-called “virtual bytes”, which map directly to on-chain fees and thus are preferred to raw bytes. For Table 2, transaction size is calculated in raw bytes instead, to better align with the counting method used in the efficiency evaluation found in [5]. We used the tool found in <https://jlopp.github.io/bitcoin-transaction-size-calculator/> to aid size calculation.

The comparison is performed both for channels of length 3 and for channels of length n . In the second comparison BCVC is not included, since only LVPC and Donner offer a way to open virtual channels of length greater than 3 (since LVPC is recursive and Donner is variadic). For a virtual channel between P_1 and P_n over $n - 1$ base channels via LVPC, we consider the case in which the funder P_1 initially has a channel with P_2 and then opens one virtual channel with party P_i on top of its channel with party P_{i-1} for $i \in \{3, \dots, n\}$. We choose this topology, as P_1 cannot assume that there exist any virtual channels between other parties (which could be used as shortcuts).

BCVC proposes 4 configurations, each with different efficiency characteristics: over Generalised Channels [4] (GC) or Lightning, and with or without validity (V or NV respectively); we include all of them here. We refer the reader to [5] for more details.

Since all constructions produce pairwise channels, updates (a.k.a. payments) always implicate exactly two parties and their interaction is independent of the number of underlying channels. Therefore the “Update” entries in Table 2 also cover the general case of n underlying channels. *Party rounds* are calculated as $[\text{\#incoming messages} + \text{\#outgoing messages}]/2$, for each party separately. Note that the update-related storage requirements of Elmo-related entries in Table 2 do not take into account savings that may arise by deleting old unneeded data at the end of an update.

Some results disagree slightly with those of the tables found in related work, due to differences in the counting method. Also note that the data for Elmo are derived assuming a virtual channel opened directly on top of $n - 1$ base channels, in other words the channel considered is opened without the help of recursion.

	Open		Update		Cooperative Close		Unilateral Close	
	#txs	size	#txs	size	#txs	size	#txs	size
BCVC-GC-NV	7	2829	2	695	4	1390	7	2829
BCVC-GC-V	8	2803	2	695	4	1390	8	2803
BCVC-LN-NV	16	7704	8	2824	4	1412	4	2153
BCVC-LN-V	14	5722	4	1412	4	1412	5	2131
Elmo	7	5245	4	1517	20	8002	4	2223

Table 2. Efficiency comparison of a 3-party channel in Elmo and BCVC [5]

In Table 3 we compare the resources needed to open a new virtual channel both for each party individually and for all parties in total, in terms of party rounds and amount of data sent and stored. The data is counted as the sum of the relevant channel identifiers (8 bytes each, as defined by the Lightning Network specification³), transaction output identifiers (36 bytes), secret keys (32 bytes each), public keys (33 bytes each, compressed form – these double as party identifiers), signatures (71 bytes each), coins (8 bytes each), times and timelocks (both 4 bytes each). UC-specific data is ignored.

³ https://github.com/lightning/bolts/blob/master/07-routing-gossip.md#definition-of-short_channel_id

In LVPC, every intermediary, apart from the first one, acts both as a fundee in a new virtual channel with the funder and as an intermediary in the funder’s virtual channel with the party after said intermediary. In Table 3 the intermediary columns contain the total cost of any intermediary that is not the first one, therefore the first intermediary (the party after the funder) incurs [intermediary’s costs - fundee’s costs] for all three measured quantities.

	Funder						Open						Total	
	party rounds	size		party rounds	size		party rounds	size		party rounds	size		size	
		sent	stored		sent	stored		sent	stored		sent	stored		
LVPC	$8(n-2)$	$1381(n-2)$	$3005(n-2)$	7	1254	2936	16	2989	6385			$4370n-8740$	$9390n-18780$	
Donner	2	$184n+829$	$1332.5k+43n+125.5$	1	$43n+192.5$	$1332.5k+43n+125.5$	1	547	$1332.5k+43n+125.5$			$774n-71$	$1332.5kn+43n^2+125.5n$	
Elmo	6	$\frac{7}{3}n^3-109n^2+\frac{1432}{3}n-325$	$33n+444$	6	$\frac{7}{3}n^3-109n^2+\frac{1336}{3}n-401$	$33n+444$	12	$\frac{106}{3}n^3-208n^2+\frac{2302}{3}n-551$	$\frac{175(i-2)n^2}{(175i^2-64i-572)n+111(i^2-i-2)}$			$\frac{106}{3}n^4-274n^3+688n^2-1162n+376$	$\frac{122}{3}n^4-281n^3+\frac{5549}{6}n^2-1181n+44$	

Table 3. Open efficiency comparison of virtual channel protocols with n parties and k payments

Unilateral Close								
	Intermediary		Funder		Fundee		Total	
	#txs	size	#txs	size	#txs	size	#txs	size
LVPC	3	627	2	383	2	359	$2n - 2$	$435n - 510.5$
Donner	1	204.5	4	$704 + 43n$	1	136.5	$2n$	$458n - 26$
Elmo	1	$594 + 27n$	2	503	2	503	n	$27n^2 + 541n - 684.5$

Table 4. On-chain worst-case closing efficiency comparison of virtual channel protocols with n parties

The on-chain number of transactions to close a virtual channel in the case of LVPC is calculated as follows: One “split” transaction is needed for each base channel ($n - 1$ in total), plus one “merge” transaction per virtual channel ($n - 2$ in total), plus a single “refund” transaction for the virtual channel, for a total of $2n - 2$ transactions.

We note that the linear size factor when the intermediary closes can, in the case of our work, be eliminated with the aid of Schnorr signatures (recently added to Bitcoin), bringing its cost below that of LVPC. This is so because the n signatures that are needed to spend each virtual output can be reduced to a single aggregate signature without compromising security. Likewise, Schnorr signatures help eliminate the quadratic term and reduce the linear term of the total on-chain cost, as well as reduce the required storage. The same cannot be said for the linear factor in Donner, since Schnorr signatures cannot optimise away the n outputs of the funder’s transaction \mathbf{tx}^{vc} . Likewise LVPC cannot gain a linear improvement with this optimisation, since each of its relevant transactions (“split”, “merge” and “refund”) needs constant signatures. We deduce that, using this optimisation, Elmo has the smallest worst-case total on-chain footprint compared to LVPC and Donner.

7 Discussion and Future work

A number of features can be added to our protocol for additional efficiency, usability and flexibility. First of all, in our current construction, each time a particular channel C acts as a base channel for a new virtual channel, one more “virtualisation layer” is added. When one of its owners wants to close C , it has to put on-chain as many transactions as there are virtualisation layers. Also the timelocks associated with closing a virtual channel increase with the number of virtualisation layers of its base channels. Both these issues can be alleviated by extending the opening and cooperative closing subprotocol with the ability to cooperatively open and close multiple virtual channels in the same layer, either simultaneously or as an amendment to an existing virtualisation layer.

Due to the possibility of the griefing attack discussed in Subsection C.3, the range of balances a virtual channel can support is limited by the balances of neighbouring channels. We believe that this limitation can be lifted if the Lightning-based construction for the payment layer is replaced with an eltoo-based [18] one. Since in eltoo a maliciously published old state can be simply re-spent by the honest latest state, the griefing attack is completely avoided. What is more, our protocol shares with eltoo the need for the `ANYPREVOUT` flag, therefore no additional requirements from Bitcoin would be added by this change. Lastly, due to the separation of intermediate layers with the payment layer in our pseudocode implementation (i.e. the distinction between the LN and the VIRT protocols), this change in principle needs only limited changes to the protocol.

As it currently stands, the timelocks calculated for the virtual channels are based on p (Figure 24) and s (Figure 28), which are global constants that are immutable and common to all parties. The parameter s stems from the liveness guarantees of Bitcoin, as discussed in Proposition 1 and therefore cannot be tweaked. However, p represents the maximum time (in blocks) between two activations of a non-negligent party, so in principle it is possible for the parties to explicitly negotiate this value when opening a new channel and even renegotiate it after the channel has been opened if the counterparties agree. We leave this usability-augmenting protocol feature as future work.

Our protocol is not designed to “gracefully” recover from a situation in which halfway through a subprotocol, one of the counterparties starts misbehaving. Currently the only solution is to unilaterally close the channel. This however means that DoS attacks (that still do not lead to channel fund losses) are possible. A practical implementation of our protocol would need to expand the available actions and states to be able to transparently and gracefully recover from such problems, avoiding closing the channel where possible, especially when the problem stems from network issues and not from malicious behaviour.

Furthermore, any deployment of the protocol has to explicitly handle the issue of transaction fees. These include miner fees for on-chain transactions and intermediary fees for the parties that own base channels and facilitate opening virtual channels. These fees should take into account the fact that each intermediary has quadratic storage requirements, whereas endpoints only need constant storage, creating an opportunity for amplification attacks. Our protocol is com-

patible with any such fee parameterization and we leave for future work the incentive analyses that can determine concrete values for such intermediary fees.

In order to increase readability and to keep focus on the salient points of the construction, our protocol does not exploit a number of possible optimisations. These include a number of techniques employed in Lightning that drastically reduce storage requirements, along with a variety of possible improvements to our novel virtual subprotocol. Most notably, the Taproot [55] feature that has been recently added to Bitcoin will allow for a drastic reduction in the size of transactions, as in the optimistic case only the hash of the Script has to be added to the blockchain and the n signatures needed to spend a virtual output can be replaced with their aggregate, resulting in constant size storage. As this work is mainly a proof of feasibility, we leave these optimisations as future work.

Additionally, our protocol does not feature one-off multi-hop payments like those possible in Lightning. This however is a useful feature in case two parties know that they will only transact once, as opening a virtual channel needs substantially more network communication than performing an one-off multi-hop payment. It would be therefore fruitful to also enable the multi-hop payment technique used in Lightning and allow human users to choose which method to use in each case. Likewise, optimistic cooperative on-chain closing of simple channels could be done just like in Lightning, obviating the need to wait for the revocation timelock to expire and reducing on-chain costs if the counterparty is cooperative.

Moreover, our need for ANYPREVOUT prevents our protocol from being deployable on Bitcoin today. Though it is a prime contender for inclusion in the next update, there is a slight chance it will never make it. Nevertheless, as mentioned before, we conjecture that a variadic virtual channel protocol with unlimited lifetime needs each party to store an exponential number of signatures if ANYPREVOUT is not available. We leave proof of this as future work.

Last but not least, the current analysis gives no privacy guarantees for the protocol, as it does not employ onion packets [17] like Lightning. Furthermore, $\mathcal{G}_{\text{Chan}}$ leaks all messages to the ideal adversary therefore theoretically no privacy is offered at all. Nevertheless, onion packets can be incorporated in the current construction and intuitively our construction leaks less data than Lightning for the same multi-hop payments, as intermediaries in our case are not notified on each payment, contrary to multi-hop payments in Lightning. Therefore a future extension can improve the privacy of the construction and formally demonstrate exact privacy guarantees.

8 Conclusion

In this work we presented Recursive Virtual Payment Channels for Bitcoin, a construction which enables the establishment and optimistic teardown of pairwise payment channels without the need for posting on-chain transactions. Such a channel can be opened over a path of consecutive base channels of arbitrary length, i.e., the virtual channel constructor is variadic.

The base channels themselves can be virtual, therefore the novel recursive nature of the construction. A key performance characteristic of our construction is that it has optimal round complexity for on-chain channel closing: a single transaction is required by any participant to turn the virtual channel into a simple one and one more transaction is needed to close it, be it an end-point or an intermediary. The two transactions can be submitted simultaneously.

We formally described the protocol in the UC setting, provided a corresponding ideal functionality and simulator and finally proved the indistinguishability of the protocol and functionality, along with the balance security properties that ensure no loss of funds for honest, non-negligent parties. This is achieved through the use of the `ANYPREVOUT` sighash flag, which is a feature that will in all likelihood be added in the next Bitcoin update and is also required by the eltoo improvement to lightning [18].

A Universal Composition Framework

In this work we embrace the Universal Composition (UC) framework [13] to model parties, network interactions, adversarial influence and corruptions, as well as formalise and prove security.

UC closely follows and expands upon the paradigm of simulation-based security [42]. For a particular real world protocol, the main goal of UC is allow us to provide a simple “interface”, the ideal world functionality, that describes what the protocol achieves in an ideal way. The functionality takes the inputs of all protocol parties and knows which parties are corrupted, therefore it normally can achieve the intention of the protocol in a much more straightforward manner. At a high level, once we have the protocol and the functionality defined, our goal is to prove that no probabilistic polynomial-time (PPT) Interactive Turing Machine (ITM) can distinguish whether it is interacting with the real world protocol or the ideal world functionality. If this is true we then say that the protocol UC-realises the functionality.

The principal contribution of UC is the following: Once a functionality that corresponds to a particular protocol is found, any other higher level protocol that internally uses the former protocol can instead use the functionality. This allows cryptographic proofs to compose and obviates the need for re-proving the security of every underlying primitive in every new application that uses it, therefore vastly improving the efficiency and scalability of the effort of cryptographic proofs.

An Interactive Turing Instance (ITI) is a single instantiation of an ITM. In UC, a number of ITIs execute and send messages to each other. At each moment only one ITI is executing (has the “execution token”) and when it sends a message to another ITI, it transfers the execution token to the receiver. Messages can be sent either locally (inputs, outputs) or over the network. There is no notion of time built in UC – the only requirement is that the total number of execution steps each ITI takes throughout the experiment is polynomial in the security parameter.

The first ITI to be activated is the environment \mathcal{E} . This can be an instance of any PPT ITM. This ITI encompasses everything that happens around the protocol under scrutiny, including the players that send instructions to the protocol. It also is the ITI that tries to distinguish whether it is in the real or the ideal world. Put otherwise, it plays the role of the distinguisher.

After activating and executing some code, \mathcal{E} may input a message to any party. If this execution is in the real world, then each party is an ITI running the protocol Π . Otherwise if the execution takes place in the ideal world, then each party is a dummy that simply relays messages to the functionality \mathcal{F} . An activated real world party then follows its code, which may instruct it to parse its input and send a message to another party via the network.

In UC the network is fully controlled by the so-called adversary \mathcal{A} , which may be any PPT ITI. Once activated by any network message, this machine can read the message contents and act adaptively, freely communicate with \mathcal{E} bidirectionally, choose to deliver the message right away, delay its delivery arbitrarily long,

even corrupt it or drop it entirely. Crucially, it can also choose to corrupt any protocol party (in other words, UC allows adaptive corruptions). Once a party is corrupted, its internal state, inputs, outputs and execution comes under the full control of \mathcal{A} for the rest of the execution. Corruptions take place covertly, so other parties do not necessarily learn which parties are corrupt. Furthermore, a corrupted party cannot become honest again.

The fact that \mathcal{A} controls the network in the real world is modelled by providing direct communication channels between \mathcal{A} and every other machine. This however poses an issue for the ideal world, as \mathcal{F} is a single party that replaces all real world parties, so the interface has to be adapted accordingly. Furthermore, if \mathcal{F} is to be as simple as possible, simulating internally all real world parties is not the way forward. This however may prove necessary in order to faithfully simulate the messages that the adversary expects to see in the real world. To solve these issues an ideal world adversary, also known as simulator \mathcal{S} , is introduced. This party can communicate freely with \mathcal{F} and completely engulfs the real world \mathcal{A} . It can therefore internally simulate real world parties and generate suitable messages so that \mathcal{A} remains oblivious to the fact that this is the ideal world. Normally messages between \mathcal{A} and \mathcal{E} are just relayed by \mathcal{S} , without modification or special handling.

From the point of view of the functionality, \mathcal{S} is untrusted, therefore any information that \mathcal{F} leaks to \mathcal{S} has to be carefully monitored by the designer. Ideally it has to be as little as possible so that \mathcal{S} does not learn more than what is needed to simulate the real world. This facilitates modelling privacy.

At any point during one of its activations, \mathcal{E} may return a binary value (either 0 or 1). The entire execution then halts. Informally, we say that Π UC-realises \mathcal{F} , or equivalently that the ideal and the real worlds are indistinguishable, if $\forall \text{PPT } \mathcal{A}, \exists \text{PPT } \mathcal{S} : \forall \text{PPT } \mathcal{E}$, the distance of the distributions over the machines' random tapes of the outputs of \mathcal{E} in the two worlds is negligibly small. Note the order of quantifiers: \mathcal{S} depends on \mathcal{A} , but not on \mathcal{E} .

B Functionality & Simulator

Functionality $\mathcal{G}_{\text{Chan}}$ – general message handling rules

- On receiving input (**msg**) by \mathcal{E} addressed to $P \in \{\text{Alice}, \text{Bob}\}$, handle it according to the corresponding rule in Fig. 9, 10, 11, 12 or 13 (if any) and subsequently send (**RELAY**, **msg**, P , \mathcal{E} , input) to \mathcal{A} .
- On receiving (**msg**) by party R addressed to $P \in \{\text{Alice}, \text{Bob}\}$ by means of **mode** $\in \{\text{output}, \text{network}\}$, handle it according to the corresponding rule in Fig. 9, 10, 11, 12 or 13 (if any) and subsequently send (**RELAY**, **msg**, P , \mathcal{E} , **mode**) to \mathcal{A} . // all messages are relayed to \mathcal{A}

- On receiving (RELAY, msg, P , R , mode) by \mathcal{A} (mode $\in \{\text{input}, \text{output}, \text{network}\}$, $P \in \{\text{Alice}, \text{Bob}\}$), relay msg to R as P by means of mode. // \mathcal{A} fully controls outgoing messages by $\mathcal{G}_{\text{Chan}}$
- On receiving (INFO, msg) by \mathcal{A} , handle (msg) according to the corresponding rule in Fig. 9, 10, 11, 12 or 13 (if any). After handling the message or after an “ensure” fails, send (HANDLED, msg) to \mathcal{A} . // (INFO, msg) messages by \mathcal{S} always return control to \mathcal{S} without any side-effect to any other ITI, except if $\mathcal{G}_{\text{Chan}}$ halts
- $\mathcal{G}_{\text{Chan}}$ keeps track of two state machines, one for each of *Alice*, *Bob*. If there are more than one suitable rules for a particular message, or if a rule matches the message for both parties, then both rule versions are executed. // the two rules act on different state machines, so the order of execution does not matter

Fig. 8.

Note that in UCGS [9], just like in UC, every message to an ITI may arrive via one of three channels: input, output and network. In the session of interest, input messages come from the environment \mathcal{E} in the real world, whereas in the ideal world each input message comes from the corresponding dummy party, which forwards it as received by \mathcal{E} . Outputs may be received from any subroutine (local or global). This means that the “sender field” of inputs and outputs cannot be tampered with by \mathcal{E} or \mathcal{A} . Network messages only come from \mathcal{A} ; they may have been sent from any machine but are relayed (and possibly delayed, reordered, modified or even dropped) by \mathcal{A} . Therefore, in contrast to inputs and outputs, network messages may have a tampered “sender field”.

Functionality $\mathcal{G}_{\text{Chan}}$ – open state machine, $P \in \{\text{Alice}, \text{Bob}\}$

- 1: On first activation: // before handing the message
- 2: $pk_P \leftarrow \perp$; $\text{balance}_P \leftarrow 0$; $\text{State}_P \leftarrow \text{UNINIT}$
- 3: $\text{enabler}_P \leftarrow \perp$ // if we are a virtual channel, the ITI of P ’s base channel
- 4: $\text{host}_P \leftarrow \perp$ // if we are a virtual channel, the ITI of the common host of this channel and P ’s base channel
- 5: On (BECAME CORRUPTED OR NEGLIGENT, P) by \mathcal{A} or on output (ENABLER USED REVOCATION) by host_P when in any state:
- 6: $\text{State}_P \leftarrow \text{IGNORED}$
- 7: On (INIT, pk) by P when $\text{State}_P = \text{UNINIT}$:
- 8: $pk_P \leftarrow pk$
- 9: $\text{State}_P \leftarrow \text{INIT}$
- 10: On (OPEN, x , “ledger”, ...) by *Alice* when $\text{State}_A = \text{INIT}$:
- 11: store x
- 12: $\text{State}_A \leftarrow \text{TENTATIVE BASE OPEN}$

```

13: On (BASE OPEN) by  $\mathcal{A}$  when  $State_A = \text{TENTATIVE BASE OPEN}$ :
14:   balance $_A \leftarrow x$ 
15:   layer $_A \leftarrow 0$ 
16:    $State_A \leftarrow \text{OPEN}$ 

17: On (BASE OPEN) by  $\mathcal{A}$  when  $State_B = \text{INIT}$ :
18:   layer $_B \leftarrow 0$ 
19:    $State_B \leftarrow \text{OPEN}$ 

20: On (OPEN,  $x$ , hops  $\neq$  "ledger", ...) by Alice when  $State_A = \text{INIT}$ :
21:   store  $x$ 
22:   enabler $_A \leftarrow \text{hops}[0].\text{left}$ 
23:   add enabler $_A$  to Alice's kindred parties
24:    $State_A \leftarrow \text{PENDING VIRTUAL OPEN}$ 

25: On output (FUNDED, host, ...) to Alice by enabler $_A$  when
     $State_A = \text{PENDING VIRTUAL OPEN}$ :
26:   host $_A \leftarrow \text{host}[0].\text{left}$ 
27:    $State_A \leftarrow \text{TENTATIVE VIRTUAL OPEN}$ 

28: On output (FUNDED, host, ...) to Bob by ITI  $R \in \{\mathcal{G}_{\text{Chan}}, \text{LN}\}$  when
     $State_B = \text{INIT}$ :
29:   enabler $_B \leftarrow R$ 
30:   add enabler $_B$  to Bob's kindred parties
31:   host $_B \leftarrow \text{host}$ 
32:    $State_B \leftarrow \text{TENTATIVE VIRTUAL OPEN}$ 

33: On (VIRTUAL OPEN) by  $\mathcal{A}$  when  $State_P = \text{TENTATIVE VIRTUAL OPEN}$ :
34:   if  $P = \text{Alice}$  then balance $_P \leftarrow x$ 
35:   layer $_P \leftarrow 0$ 
36:    $State_P \leftarrow \text{OPEN}$ 

```

Fig. 9. State machine in Fig. 14, 15, 16 and 21

Functionality $\mathcal{G}_{\text{Chan}}$ – payment state machine, $P \in \{\text{Alice}, \text{Bob}\}$

```

1: On (PAY,  $x$ ) by  $P$  when  $State_P = \text{OPEN}$ : //  $P$  pays  $\bar{P}$ 
2:   store  $x$ 
3:    $State_P \leftarrow \text{TENTATIVE PAY}$ 

4: On (PAY) by  $\mathcal{A}$  when  $State_P = \text{TENTATIVE PAY}$ : //  $P$  pays  $\bar{P}$ 

```

```

5:    $State_P \leftarrow (\text{SYNC PAY}, x)$ 

6: On (GET PAID,  $y$ ) by  $P$  when  $State_P = \text{OPEN}$ : //  $\bar{P}$  pays  $P$ 
7:   store  $y$ 
8:    $State_P \leftarrow \text{TENTATIVE GET PAID}$ 

9: On (PAY) by  $\mathcal{A}$  when  $State_P = \text{TENTATIVE GET PAID}$ : //  $\bar{P}$  pays  $P$ 
10:   $State_P \leftarrow (\text{SYNC GET PAID}, x)$ 

11: When  $State_P = (\text{SYNC PAY}, x)$ :
12:   if  $State_{\bar{P}} \in \{\text{IGNORED}, (\text{SYNC GET PAID}, x)\}$  then
13:      $balance_P \leftarrow balance_P - x$ 
14:     // if  $\bar{P}$  honest, this state transition happens simultaneously with l. 21
15:      $State_P \leftarrow \text{OPEN}$ 
16:   end if

17: When  $State_P = (\text{SYNC GET PAID}, x)$ :
18:   if  $State_{\bar{P}} \in \{\text{IGNORED}, (\text{SYNC PAY}, x)\}$  then
19:      $balance_P \leftarrow balance_P + x$ 
20:     // if  $\bar{P}$  honest, this state transition happens simultaneously with l. 15
21:      $State_P \leftarrow \text{OPEN}$ 
22:   end if

```

Fig. 10. State machine in Fig. 17

Functionality $\mathcal{G}_{\text{Chan}}$ – funding state machine, $P \in \{\text{Alice}, \text{Bob}\}$

```

1: On input (FUND ME,  $x, \dots$ ) by ITI  $R \in \{\mathcal{G}_{\text{Chan}}, \text{LN}\}$  when  $State_P = \text{OPEN}$ :
2:   store  $x$ 
3:   add  $R$  to  $P$ 's kindred parties
4:    $State_P \leftarrow \text{PENDING FUND}$ 

5: When  $State_P = \text{PENDING FUND}$ :
6:   if we intercept the command “define new VIRT ITI host” by  $\mathcal{A}$ , routed
   through  $P$  then
7:     store host
8:      $State_P \leftarrow \text{TENTATIVE FUND}$ 
9:     continue executing  $\mathcal{A}$ 's command
10:  end if

11: On (FUND) by  $\mathcal{A}$  when  $State_P = \text{TENTATIVE FUND}$ :
12:   $State_P \leftarrow \text{SYNC FUND}$ 

```

```

13: When  $State_P = \text{OPEN}$ :
14:   if we intercept the command “define new VIRT ITI host” by  $\mathcal{A}$ , routed
    through  $P$  then
15:     store host
16:      $State_P \leftarrow \text{TENTATIVE HELP FUND}$ 
17:     continue executing  $\mathcal{A}$ ’s command
18:   end if
19:   if we receive a RELAY message with  $\text{msg} = (\text{INIT}, \dots, \text{fundee})$  addressed
    from  $P$  by  $\mathcal{A}$  then
20:     add fundee to  $P$ ’s kindred parties
21:     continue executing  $\mathcal{A}$ ’s command
22:   end if

23: On (FUND) by  $\mathcal{A}$  when  $State_P = \text{TENTATIVE HELP FUND}$ :
24:    $State_P \leftarrow \text{SYNC HELP FUND}$ 

25: When  $State_P = \text{SYNC FUND}$ :
26:   if  $State_{\bar{P}} \in \{\text{IGNORED}, \text{SYNC HELP FUND}\}$  then
27:      $\text{balance}_P \leftarrow \text{balance}_P - x$ 
28:      $\text{host}_P \leftarrow \text{host}$ 
29:     // if  $\bar{P}$  honest, this state transition happens simultaneously with l. 38
30:      $\text{layer}_P \leftarrow \text{layer}_P + 1$ 
31:      $State_P \leftarrow \text{OPEN}$ 
32:   end if

33: When  $State_P = \text{SYNC HELP FUND}$ :
34:   if  $State_{\bar{P}} \in \{\text{IGNORED}, \text{SYNC FUND}\}$  then
35:      $\text{host}_P \leftarrow \text{host}$ 
36:     // if  $\bar{P}$  honest, this state transition happens simultaneously with l. 31
37:      $\text{layer}_P \leftarrow \text{layer}_P + 1$ 
38:      $State_P \leftarrow \text{OPEN}$ 
39:   end if

```

Fig. 11. State machine in Fig. 18

Functionality $\mathcal{G}_{\text{Chan}}$ – force close state machine, $P \in \{\text{Alice}, \text{Bob}\}$

- 1: On (FORCECLOSE) by P when $State_P = \text{OPEN}$:
- 2: $State_P \leftarrow \text{CLOSING}$
- 3: On input (BALANCE) by R addressed to P where R is kindred with P :


```

4:   if  $State_P \notin \{\text{UNINIT}, \text{INIT}, \text{PENDING VIRTUAL OPEN}, \text{TENTATIVE VIRTUAL OPEN}, \text{TENTATIVE BASE OPEN}, \text{IGNORED}, \text{CLOSED}\}$  then
5:     reply (MY BALANCE,  $\text{balance}_P$ ,  $pk_P$ ,  $\text{balance}_{\bar{P}}$ ,  $pk_{\bar{P}}$ )
6:   else
7:     reply (MY BALANCE, 0,  $pk_P$ , 0,  $pk_{\bar{P}}$ )
8:   end if

9: On (FORCECLOSE,  $P$ ) by  $\mathcal{A}$  when  $State_P \notin \{\text{UNINIT}, \text{INIT}, \text{PENDING VIRTUAL OPEN}, \text{TENTATIVE VIRTUAL OPEN}, \text{TENTATIVE BASE OPEN}, \text{IGNORED}\}$ :
10:  input (READ) to  $\mathcal{G}_{\text{Ledger}}$  as  $P$  and assign output to  $\Sigma$ 
11:   $\text{coins} \leftarrow$  sum of values of outputs exclusively spendable or spent by  $pk_P$  in  $\Sigma$ 
12:   $\text{balance} \leftarrow \text{balance}_P$ 
13:  for all  $P$ 's kindred parties  $R$  do
14:    input (BALANCE) to  $R$  as  $P$  and extract  $\text{balance}_R$ ,  $pk_R$  from response
15:     $\text{balance} \leftarrow \text{balance} + \text{balance}_R$ 
16:     $\text{coins} \leftarrow \text{coins} +$  sum of values of outputs exclusively spendable or
    spent by  $pk_R$  in  $\Sigma$ 
17:  end for
18:  if  $\text{coins} \geq \text{balance}$  then
19:     $State_P \leftarrow \text{CLOSED}$ 
20:  else // balance security is broken
21:    halt
22:  end if

```

Fig. 12.

Functionality $\mathcal{G}_{\text{Chan}}$ – cooperative close state machine, $P \in \{\text{Alice}, \text{Bob}\}$

```

1: On (COOP CLOSING,  $P$ ,  $x$ ) by  $\mathcal{A}$  when  $State_P = \text{OPEN}$ :
2:   store  $x$ 
3:    $State_P \leftarrow \text{COOP CLOSING}$ 

4: On (COOP CLOSED,  $P$ ) by  $\mathcal{A}$  when  $State_P = \text{COOP CLOSING}$ :
5:   if  $\text{layer}_P = 0$  then //  $P$ 's channel, which is virtual, is cooperatively closed
6:      $State_P \leftarrow \text{COOP CLOSED}$ 
7:   else // the virtual channel for which  $P$ 's channel is base is cooperatively
    closed
8:      $\text{layer}_P \leftarrow \text{layer}_P - 1$ 
9:      $\text{balance}_P \leftarrow \text{balance}_P + x$ 
10:     $State_P \leftarrow \text{OPEN}$ 
11:   end if

```

Fig. 13.

C Model & Construction

C.1 Model

In this section we will examine the architecture and the details of our model, along with possible attacks and their mitigations. We follow the UCGS framework [9] to formulate the protocol and its security. We list the ideal-world global functionality $\mathcal{G}_{\text{Chan}}$ in Section B (Figures 8-12) and a simulator \mathcal{S} (Figures 22-23), along with a real-world protocol Π_{Chan} (Figures 24-64) that UC-realizes $\mathcal{G}_{\text{Chan}}$ (Theorem 2). We give a self-contained description in this section, while pointing to figures in Sections B and D, in case the reader is interested in a pseudocode style specification.

As in previous formulations, (e.g., [34]), the role of \mathcal{E} corresponds to two distinct actors in a real world implementation. On the one hand \mathcal{E} passes inputs that correspond to the desires of human users (e.g. open a channel, pay, close), on the other hand \mathcal{E} is responsible with periodically waking up parties to check the ledger and act upon any detected counterparty misbehaviour, similar to an always-on “daemon” of real-life software that periodically nudges the implementation to perform these checks.

Since it is possible that \mathcal{E} fails to wake up a party often enough, Π_{Chan} explicitly checks whether it has become “negligent” every time it is activated and all security guarantees are conditioned on the party not being negligent. A party is deemed negligent if more than p blocks have been added to $\mathcal{G}_{\text{Ledger}}$ between any consecutive pair of activations. The need for explicit negligence checking stems from the fact that party activation is entirely controlled by \mathcal{E} and no synchrony limitations are imposed (e.g. via the use of $\mathcal{G}_{\text{Clock}}$), therefore it can happen that an otherwise honest party is not activated in time to prevent a malicious counterparty from successfully using an old commitment transaction. If a party is marked as negligent, no balance security guarantees are given (c.f. Lemma 1). Note that in realistic software the aforementioned daemon is local and trustworthy, therefore it would never allow Π_{Chan} to become negligent, as long as the machine is powered on and in good order.

C.2 Ideal world functionality $\mathcal{G}_{\text{Chan}}$

Our ideal world functionality $\mathcal{G}_{\text{Chan}}$ represents a single channel, either simple or virtual. It acts as a relay between \mathcal{A} and \mathcal{E} , leaking all messages. This simplifies the functionality and facilitates the indistinguishability argument by having \mathcal{S} simply running internally the real world protocols of the channel parties Π_{Chan} with no modifications. Furthermore, the communication of parties with $\mathcal{G}_{\text{Ledger}}$ is handled by $\mathcal{G}_{\text{Chan}}$: when a simulated honest party in \mathcal{S} needs to send a message to $\mathcal{G}_{\text{Ledger}}$, \mathcal{S} instructs $\mathcal{G}_{\text{Chan}}$ to send this message to $\mathcal{G}_{\text{Ledger}}$ on this party’s

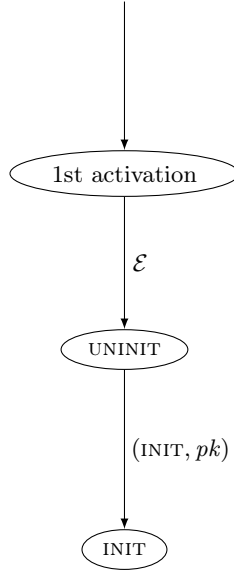


Fig. 14. $\mathcal{G}_{\text{Chan}}$ state machine up to INIT (both parties)

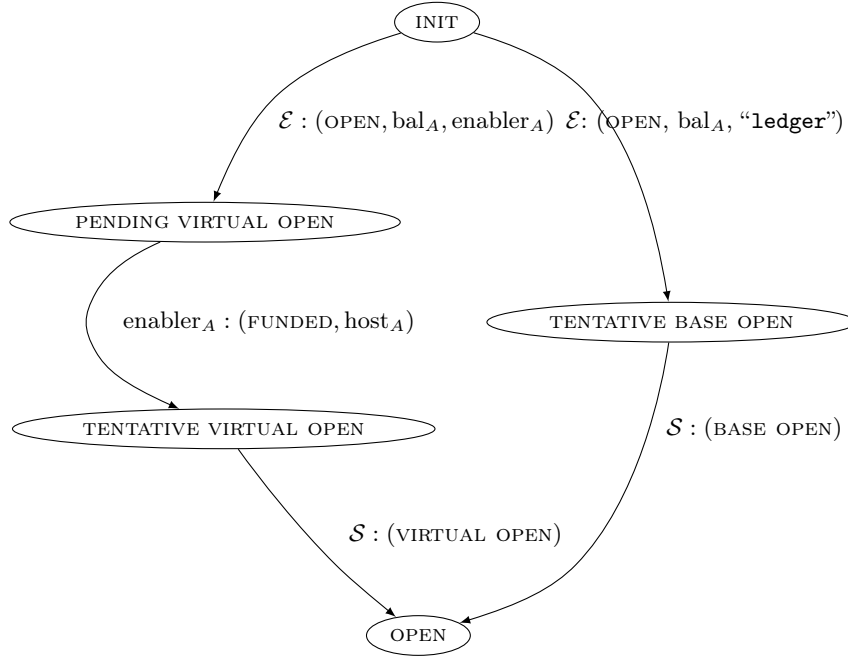


Fig. 15. $\mathcal{G}_{\text{Chan}}$ state machine from INIT up to OPEN (funder)

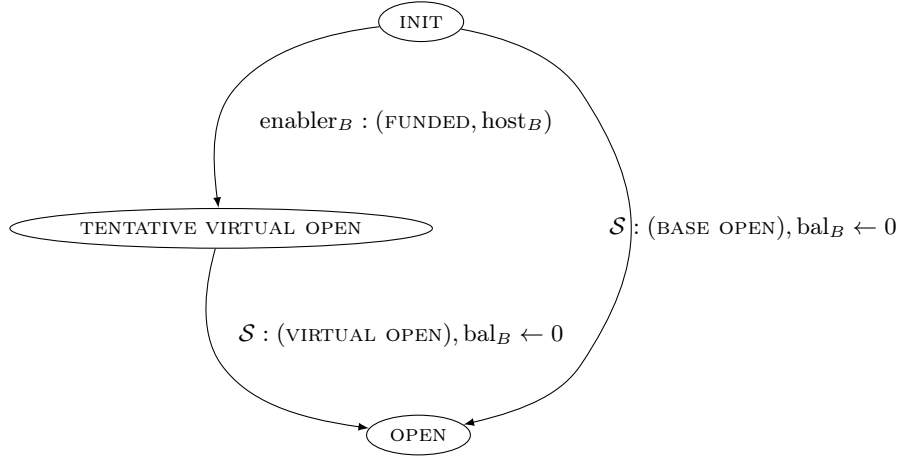


Fig. 16. $\mathcal{G}_{\text{Chan}}$ state machine from INIT up to OPEN (fundee)

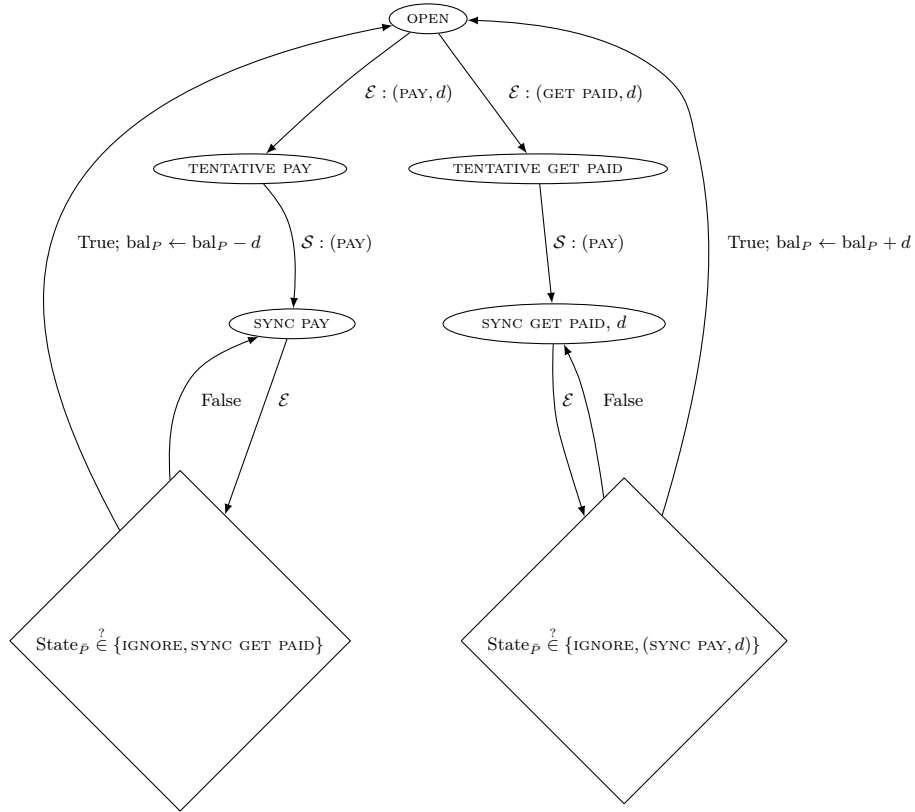


Fig. 17. $\mathcal{G}_{\text{Chan}}$ state machine for payments (both parties)

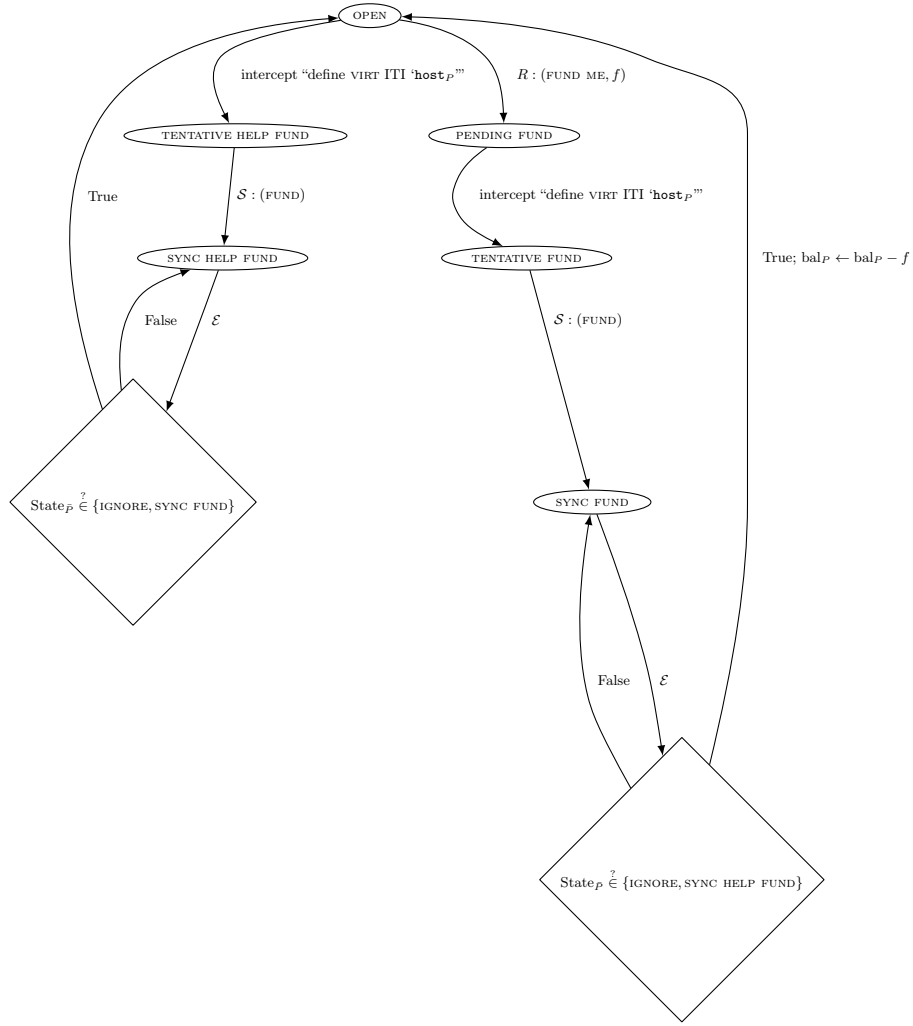


Fig. 18. $\mathcal{G}_{\text{Chan}}$ state machine for funding new virtuals (both parties)

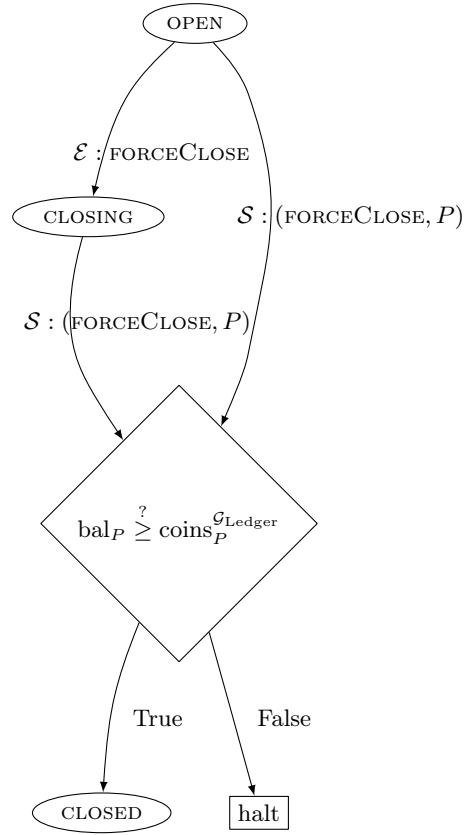


Fig. 19. $\mathcal{G}_{\text{Chan}}$ state machine for channel closure (both parties)

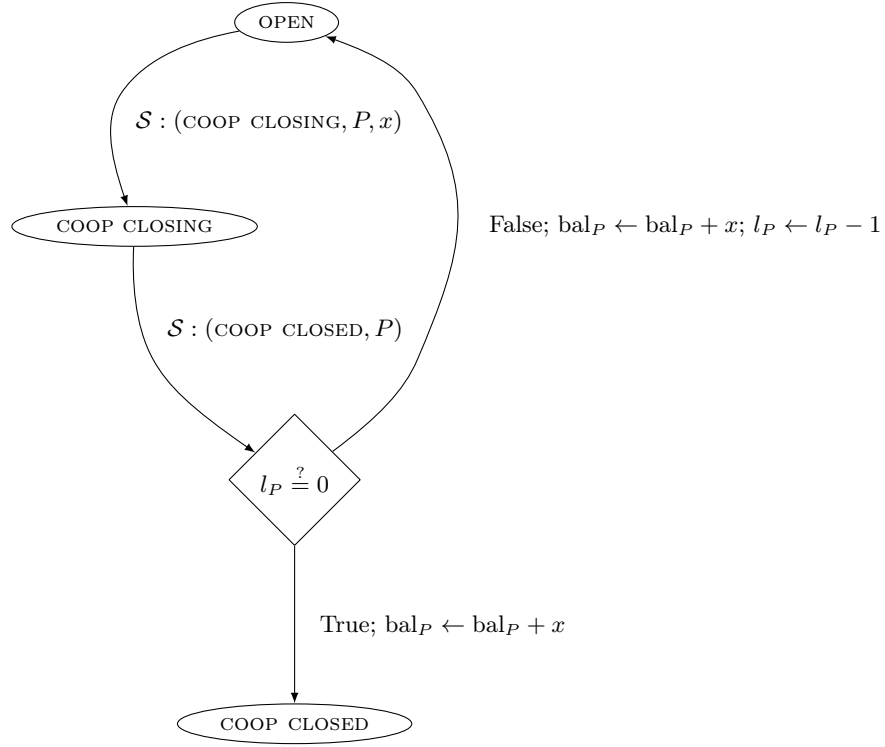


Fig. 20. $\mathcal{G}_{\text{Chan}}$ state machine for cooperative channel closure (all parties)

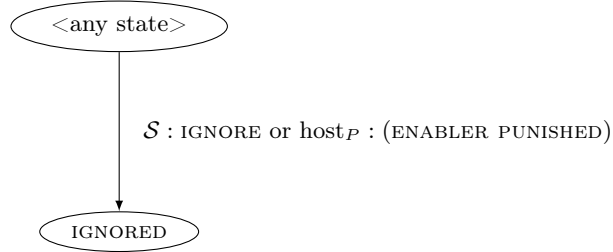


Fig. 21. $\mathcal{G}_{\text{Chan}}$ state machine for corruption, negligence or punishment of the counterparty of a lower layer (both parties)

behalf. $\mathcal{G}_{\text{Chan}}$ internally maintains two state machines, one per channel party (c.f. Figures 14, 15, 16, 18, 17, 19, 21) that keep track of whether the parties are corrupted or negligent, whether the channel has opened, whether a payment is underway, which ITIs are to be considered *kindred* parties (as they correspond to other channels owned by the same human user, discussed below) and whether the channel is currently closing collaboratively or has already closed. The single security check performed is *whether the on-chain coins are at least equal to the expected balance once the channel closes*. If this check fails, $\mathcal{G}_{\text{Chan}}$ halts. Since the protocol Π_{Chan} (which realises $\mathcal{G}_{\text{Chan}}$, c.f. Theorems 1 and 2) never halts, this ideal world check corresponds to the security guarantee offered by Π_{Chan} . Note that this check is not performed for negligent parties, as \mathcal{S} notifies $\mathcal{G}_{\text{Chan}}$ if a party becomes negligent and the latter omits the check. Thus indistinguishability between the real and the ideal world is not violated in case of negligence.

Observe that a human user may participate in various channels, therefore it corresponds to more than one ITMs. This is the case for example for the funder of a virtual channel and the corresponding party of the first base channel. Such parties are called *kindred*. They communicate locally (i.e. via inputs and outputs, without using the adversarially controlled network) and balance guarantees concern their aggregate coins. Formally this communication is modelled by having a virtual channel using its base channels as global subroutines, as defined in [9].

If we were using plain UC, the above would constitute a violation of the subroutine respecting property that functionalities have to fulfill. We leverage the concept of global functionalities put forth in [9] to circumvent the issue. More specifically, we say that a simple channel functionality is of “level” 1, which is written as $\mathcal{G}_{\text{Chan}}^1$. Inductively, a virtual channel functionality that is based on channels of any “level” up to and including $n - 1$ has a “level” n , which we write as $\mathcal{G}_{\text{Chan}}^n$. Then $\mathcal{G}_{\text{Chan}}^n$ is $(\mathcal{G}_{\text{Ledger}}, \mathcal{G}_{\text{Chan}}^1, \dots, \mathcal{G}_{\text{Chan}}^{n-1})$ -subroutine respecting, according to the definition of [9]. The same structure is used in the real world between protocols. This technique ensures that the necessary conditions for the validity of the functionality and the protocol are met and that the realisability proof can go through, as we will see in Section 5 in more detail.

We could instead contain all the channels in a single, monolithic functionality (following the approach of [34]) and we believe that we could still carry out the security proof. Nevertheless, having the functionality correspond to a single channel has no drawbacks, as all desired security guarantees are provided by our modular architecture, and instead brings two benefits. Firstly, the functionality is easier to intuitively grasp, as it handles less tasks. Having a simple and intuitive functionality aids in its reusability and is an informal goal of the simulation-based paradigm. Secondly, this approach permits our functionality to be global, as defined in [9]. We note that the ideal functionality defined in [4] is unsuitable for our case, as it requires direct access to the ledger, which is not the case for a $\mathcal{G}_{\text{Chan}}$ corresponding to a virtual channel.

C.3 Real world protocol Π_{Chan}

Our real world protocol Π_{Chan} , ran by party P , consists of two subprotocols: the Lightning-inspired part, dubbed LN (Figures 24-43) and the novel virtual layer subprotocol, named VIRT (Figures 49-64). A simple channel that is not the base of any virtual channel leverages only LN, whereas a simple channel that is the base of at least one virtual channel does leverage both LN and VIRT. A virtual channel uses both LN and VIRT.

LN subprotocol The LN subprotocol has two variations depending on whether P is the channel funder (*Alice*) or the fundee (*Bob*). It performs a number of tasks: Initialisation takes a single step for fundees and two steps for funders. LN first receives a public key $pk_{P,\text{out}}$ from \mathcal{E} . This is the public key that should eventually own all P 's coins after the channel is closed. LN also initialises its internal variables. If P is a funder, LN waits for a second activation to generate a keypair and then waits for \mathcal{E} to endow it with some coins, which will be subsequently used to open the channel (Figure 24).

After initialisation, the funder *Alice* is ready to open the channel. Once \mathcal{E} gives to *Alice* the identity of *Bob*, the initial channel balance c and, (looking forward to the VIRT subprotocol description) in case it is a virtual channel, the identities of the base channel owners (Figure 31), *Alice* generates and sends *Bob* her funding and revocation public keys ($pk_{A,F}$, $pk_{A,R}$, used for the funding and revocation outputs respectively) along with c , $pk_{A,\text{out}}$, and the base channel identities (only for virtual channels). Given that *Bob* has been initialised, it generates funding and revocation keys and replies to *Alice* with $pk_{B,F}$, $pk_{B,R}$, and $pk_{B,\text{out}}$ (Figure 26).

The next step prepares the base channels (Figure 27) if needed. If our channel is a simple one, then *Alice* simply generates the funding tx. If it is a virtual and assuming all base parties (running LN) cooperate, a chain of messages from *Alice* to *Bob* and back via all base parties is initiated (Figures 33 and 34). These messages let each successive neighbour know the identities of all the base parties. Furthermore each party instantiates a new “host” party that runs VIRT. It also generates new funding keys and communicates them, along with its “out” key $pk_{P,\text{out}}$ and its leftward and rightward balances. If this circuit of messages completes, *Alice* delegates the creation of the new virtual layer transactions to its new VIRT host, which will be discussed later in detail. If the virtual layer is successful, each base party is informed by its host accordingly, intermediaries return to the OPEN state (i.e., they have completed their part and are in standby, ready to accept instructions for, e.g., new payments) and *Alice* and *Bob* continue the opening procedure. In particular, *Alice* and *Bob* exchange signatures on the initial commitment transactions, therefore ensuring that the funding output can be spent (Figure 28). After that, in case the channel is simple the funding transaction is put on-chain (Figure 29) and finally \mathcal{E} is informed of the successful channel opening.

There are two facts that should be noted: Firstly, in case the opened channel is virtual, each intermediary necessarily partakes in two channels. However

each protocol instance only represents a party in a single channel, therefore each intermediary is in practice realised by two kindred Π_{Chan} instances that communicate locally, called “siblings”. Secondly, our protocol is not designed to gracefully recover if other parties do not send an expected message at any point in the opening or payment procedure. Such anti-Denial-of-Service measures would greatly complicate the protocol and are left as a task for a real world implementation. It should however be stressed that an honest party with an open channel that has fallen victim to such an attack can still unilaterally close the channel, therefore no coins are lost in any case.

Once the channel is open, *Alice* and *Bob* can carry out an unlimited number of payments in either direction, only needing to exchange 3 direct network messages with each other per payment, therefore avoiding the slow and costly on-chain validation. The payment procedure is identical for simple and virtual channels and crucially it does not implicate the intermediaries (and therefore *Alice* and *Bob* do not incur any delays such an interaction with intermediaries would introduce). For a payment to be carried out, the payee is first notified by \mathcal{E} (Figure 38) and subsequently the payer is instructed by \mathcal{E} to commence the payment (Figure 37).

If the channel is virtual, each party also checks that its upcoming balance is lower than the balance of its sibling’s counterparty and that the upcoming balance of the counterparty is higher than the balance of its own sibling, otherwise it rejects the payment. This is to mitigate a “griefing” attack (i.e. one that does not lead to financial gain) where a malicious counterparty uses an old commitment transaction to spend the base funding output, therefore blocking the honest party from using its initiator virtual transaction. This check ensures that the coins gained by the punishment are sufficient to cover the losses from the blocked initiator transaction. If the attack takes place, other local channels based directly or indirectly on it are informed and are moved to a failed state. Note that this does not bring a risk of losing any of the total coins of all local channels. We conjecture that this balance constraint can be lifted if the current Lightning-inspired payment method is replaced with an eltoo-inspired one [18].

Subsequently each of the two parties builds the new commitment transaction of its counterparty and signs it. It also generates a new revocation keypair for the next update and sends over the generated signature and public key. Then the revocation transactions for the previously valid commitment transactions are generated, signed and the signatures are exchanged. To reduce the number of messages, the payee sends the two signatures and the public key in one message. This does not put it at risk of losing funds, since the new commitment transaction (for which it has already received a signature and therefore can spend) gives it more funds than the previous one.

Π_{Chan} also checks the chain for outdated commitment transactions by the counterparty and publishes the corresponding revocation transaction in case one is found (Figure 40). It also keeps track of whether the party is activated often enough and marks it as negligent otherwise (Figure 24). In particular, at the beginning of every activation while the channel is open, LN checks if the

party has been activated within the last p blocks (where p is an implementation-dependent global constant) by reading from $\mathcal{G}_{\text{Ledger}}$ and comparing the current block height with that of the last activation.

Cooperative closing involves both LN (Figures 44-47) and VIRT (Figure 63) subprotocols. Any party can initiate it by asking the virtual channel fundee. The latter signs the last coin balance and sends it to the funder, who first ensures the fundee signed the correct balance, then signs it as well. Its enabler (i.e. the kindred party that is a member of the 1st base channel) generates and signs a new commitment tx in which it adds the funder's coins to its own and the fundee's coins to its counterparty's, while using the funding keys that were used before opening the virtual channel. It also generates a new revocation keypair for the next channel update and sends the revocation public key with the signature and the final virtual channel balance to its counterparty. The latter verifies the signature and that the two virtual channel parties agree on their final balance. If all goes well, it passes control to its kindred party that is a member of the next channel in sequence. If no verification fails, the process repeats until the fundee is reached. Now a backwards sequence of messages begins, in which each party that previously did verification now provides a signature for the new commitment tx, along with a revocation signature for the old commitment tx and a new revocation public key for the next update. Each receiver verifies the signatures and "passes the baton" to its kindred party closer to the funder. When the funder is reached, the last series of messages begins. Now each party that has not yet sent a revocation does so. Once the chain of messages reaches the fundee, the channel has successfully closed cooperatively. In total, each LN party sends and stores 2 signatures, 1 private key and 1 public key. The associated behaviour of the VIRT subprotocol is discussed later.

Alternatively, when either party is instructed by \mathcal{E} to unilaterally close the channel (Figure 42), it first asks its host to unilaterally close (details on the exact steps are discussed later) and once that is done, the ledger is checked for any transaction spending the funding output. In case the latest remote commitment tx is on-chain, then the channel is already closed and no further action is necessary. If an old commitment transaction is on-chain, the corresponding revocation transaction is used for punishment. If the funding output is still unspent, the party attempts to publish the latest commitment transaction after waiting for any relevant timelock to expire. Until the funding output is irrevocably spent, the party still has to periodically check the blockchain and again be ready to use a revocation transaction if an old commitment transaction spends the funding output after all (Figure 40).

VIRT subprotocol This subprotocol acts as a mediator between the base channels and the Lightning-based logic. Put simply, its main responsibility is putting on-chain the funding output of the channel when needed. When first initialised by a machine that executes the LN subprotocol (Figure 49), it learns and stores the identities, keys, and balances of various relevant parties, along with the required timelock and other useful data regarding the base channels. It then generates a number of keys as needed for the rest of the base preparation. If the initialiser

is also the channel funder, then the VIRT machine initiates 4 “circuits” of messages. Each circuit consists of one message from the funder P_1 to its neighbour P_2 , one message from each intermediary P_i to the “next” neighbour P_{i+1} , one message from the fundee P_n to its neighbour P_{n-1} and one more message from each intermediary P_i to the “previous” neighbour P_{i-1} , for a total of $2 \cdot (n - 1)$ messages per circuit.

The first circuit (Figure 50) communicates all “out”, virtual, revocation and funding keys (both old and new), all balances and all timelocks among all parties. In the second circuit (Figure 57) every party receives and verifies all signatures for all inputs of its virtual transactions that spend a virtual output. It also produces and sends its own such signatures to the other parties. Each party generates

and circulates $S = \sum_{i=2}^{n-2} (n-3+\chi_{i=2}+\chi_{i=n-1}+2(i-2+\chi_{i=2})(n-i-1+\chi_{i=n-1})) \in$

$O(n^3)$ signatures (where χ_A is the characteristic function that equals 1 if A is true and 0 else), which is derived by calculating the total number of virtual outputs of all parties’ virtual transactions – we remind that each virtual output can be spent by a n -of- n multisig. On a related note, the number of virtual transactions for which each party needs to store signatures is 1 for the two endpoints (Figure 52) and $n-2+\chi_{i=2}+\chi_{i=n-1}+(i-2+\chi_{i=2})(n-i-1+\chi_{i=n-1}) \in O(n^2)$ for the i -th intermediary (Figure 51). The latter is derived by counting the number of extend-interval and merge-intervals transactions held by the intermediary, which are equal to the number of distinct intervals that the party can extend and the number of distinct pairs of intervals that the party can merge respectively, plus 1 for the unique initiator transaction of the party. The third circuit concerns sharing signatures for the funding outputs (Figure 58). Each party signs all transactions that spend a funding output relevant to the party, i.e. the initiator transaction and some of the extend-interval transactions of its neighbours. The two endpoints send 2 signatures each when $n = 3$ and $n-2$ signatures each when $n > 3$, whereas each intermediary sends $2+\chi_{i+1 < n}(n-2+\chi_{i=n-2})+\chi_{i-1 > 1}(n-2+\chi_{i=3}) \in O(n)$ signatures each. The last circuit of messages (Figure 59) carries the revocations of the previous states of all base channels. After this, base parties can only use the newly created virtual transactions to spend their funding outputs. In this step each party exchanges a single signature with each of its neighbours.

In case of a cooperative closing, VIRT orchestrates the hosted LN ITIs, instructing them to perform the actions discussed previously. It also is responsible for sending the actual messages to the host of the next counterparty and receiving its responses. Apart from controlling the flow of messages, a VIRT ITI also generates revocation signatures to invalidate its virtual transactions and verifies the respective revocation signatures generated by its counterparty VIRT ITI, thereby ensuring that, moving forward, the use of an old virtual transaction can be punished.

On the other hand, when VIRT is instructed to unilaterally close by party R (Figure 61), it first notifies its VIRT host (if any) and waits for it to unilaterally close. After that, it signs and publishes the unique valid virtual transaction. It then repeatedly checks the chain to see if the transaction is included

(Figure 62). If it is included, the virtual layer is closed and VIRT informs (i.e. outputs (CLOSED) to) R . The instruction to close has to be received potentially many times, because a number of virtual transactions (the ones that spend the same output) are mutually exclusive and therefore if another base party publishes an incompatible virtual transaction contemporaneously and that remote transaction wins the race to the chain, then our VIRT party has to try again with another, compatible virtual transaction.

Simulator \mathcal{S} – general message handling rules

- On receiving (RELAY, in_msg , P , R , in_mode) by $\mathcal{G}_{\text{Chan}}$ ($\text{in_mode} \in \{\text{input, output, network}\}$, $P \in \{\text{Alice, Bob}\}$), handle (in_msg) with the simulated party P as if it was received from R by means of in_mode . In case simulated P does not exist yet, initialise it as an LN ITI. If there is a resulting message out_msg that is to be sent by simulated P to R' by means of $\text{out_mode} \in \{\text{input, output, network}\}$, send (RELAY, out_msg , P , R' , out_mode) to $\mathcal{G}_{\text{Chan}}$.
- On receiving by $\mathcal{G}_{\text{Chan}}$ a message to be sent by P to R via the network, carry on with this action (i.e. send this message via the internal \mathcal{A}).
- Relay any other incoming message to the internal \mathcal{A} unmodified.
- On receiving a message (msg) by the internal \mathcal{A} , if it is addressed to one of the parties that correspond to $\mathcal{G}_{\text{Chan}}$, handle the message internally with the corresponding simulated party. Otherwise relay the message to its intended recipient unmodified. // Other recipients are \mathcal{E} , $\mathcal{G}_{\text{Ledger}}$ or parties unrelated to $\mathcal{G}_{\text{Chan}}$.

Given that $\mathcal{G}_{\text{Chan}}$ relays all messages and that we simulate the real-world machines that correspond to $\mathcal{G}_{\text{Chan}}$, the simulation is perfectly indistinguishable from the real world.

Fig. 22.

Simulator \mathcal{S} – notifications to $\mathcal{G}_{\text{Chan}}$

- “ P ” refers one of the parties that correspond to $\mathcal{G}_{\text{Chan}}$.
 - When an action in this Figure interrupts an ITI simulation, continue simulating from the interruption location once action is over/ $\mathcal{G}_{\text{Chan}}$ hands control back.
- 1: On (CORRUPT) by \mathcal{A} , addressed to P :
 - 2: // After executing this code and getting control back from $\mathcal{G}_{\text{Chan}}$ (which always happens, c.f. Fig. 8), deliver (CORRUPT) to simulated P (c.f. Fig. 22).
 - 3: send (INFO, BECAME CORRUPTED OR NEGLIGENT, P) to $\mathcal{G}_{\text{Chan}}$
 - 4: When simulated P sets variable **negligent** to True (Fig. 24, l. 7/Fig. 25, l. 26):
 - 5: send (INFO, BECAME CORRUPTED OR NEGLIGENT, P) to $\mathcal{G}_{\text{Chan}}$

6: When simulated honest *Alice* receives (OPEN, x , hops, ...) by \mathcal{E} :

7: store hops // will be used to inform $\mathcal{G}_{\text{Chan}}$ once the channel is open

8: When simulated honest *Bob* receives (OPEN, x , hops, ...) by *Alice*:

9: **if** *Alice* is corrupted **then** store hops // if *Alice* is honest, we already have hops. If *Alice* became corrupted after receiving (OPEN, ...), overwrite hops

10: When the last of the honest simulated $\mathcal{G}_{\text{Chan}}$'s parties moves to the OPEN State for the first time (Fig. 28, l. 19/Fig. 30, l. 16/Fig. 31, l. 18):

11: **if** hops = "ledger" **then**

12: send (INFO, BASE OPEN) to $\mathcal{G}_{\text{Chan}}$

13: **else**

14: send (INFO, VIRTUAL OPEN) to $\mathcal{G}_{\text{Chan}}$

15: **end if**

16: When (both $\mathcal{G}_{\text{Chan}}$'s simulated parties are honest and complete sending and receiving a payment (Fig. 36, ll. 6 and 21 respectively), or (when only one party is honest and (completes either receiving or sending a payment)): // also send this message if both parties are honest when Fig. 36, l. 6 is executed by one party, but its counterparty is corrupted before executing Fig. 36, l. 21

17: send (INFO, PAY) to $\mathcal{G}_{\text{Chan}}$

18: When honest P executes Fig. 33, l. 21 or (when honest P executes Fig. 33, l. 19 and \bar{P} is corrupted): // in the first case if \bar{P} is honest, it has already moved to the new host, (Fig 59, ll. 7, 23): lifting to next layer is done

19: send (INFO, FUND) to $\mathcal{G}_{\text{Chan}}$

20: When one of the honest simulated $\mathcal{G}_{\text{Chan}}$'s parties P moves to the COOP CLOSING state (Fig. 46, l. 4, Fig. 47, ll. 6, 12, Fig. 63, ll. 11, 24):

21: **if** triggered by Fig. 46, l. 4 or Fig. 47, l. 6 **then** // P is funder or fundee

22: send (INFO, COOP CLOSING, P , $-c_P$) to $\mathcal{G}_{\text{Chan}}$ // coin value extracted from simulated P

23: **else if** triggered by Fig. 47, l. 12 **then** // P is funder's base

24: send (INFO, COOP CLOSING, P , c'_1) to $\mathcal{G}_{\text{Chan}}$

25: **else if** triggered by Fig. 63, l. 11 **then** // P is an intermediary farther from funder than \bar{P}

26: send (INFO, COOP CLOSING, P , c'_2) to $\mathcal{G}_{\text{Chan}}$

27: **else if** triggered by Fig. 63, l. 24 **then** // P is an intermediary closer to funder than \bar{P}

28: send (INFO, COOP CLOSING, P , $c'_1 - c_{\text{virt}}$) to $\mathcal{G}_{\text{Chan}}$

29: **end if**

30: When one of the honest simulated $\mathcal{G}_{\text{Chan}}$'s parties P completes cooperative closing (Fig. 47, l. 45, Fig. 63, l. 187, Fig. 63, l. 150, Fig. 63, or l. 134):

31: send (INFO, COOP CLOSED, P) to $\mathcal{G}_{\text{Chan}}$

```

32: When one of the honest simulated  $\mathcal{G}_{\text{Chan}}$ 's parties  $P$  moves to the CLOSED
    state (Fig. 40, l. 8 or l. 11):
33:   send (INFO, FORCECLOSE,  $P$ ) to  $\mathcal{G}_{\text{Chan}}$ 

```

Fig. 23.

D Protocol

Process LN – init

```

1: // When not specified, input comes from and output goes to  $\mathcal{E}$ .
2: // The ITI knows whether it is Alice (funder) or Bob (fundee). The activated
   party is  $P$  and the counterparty is  $\bar{P}$ .
3: On every activation, before handling the message:
4:   if  $\text{last\_poll} \neq \perp \wedge \text{State} \neq \text{CLOSED}$  then // channel is open
5:     input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
6:     if  $\text{last\_poll} + p < |\Sigma|$  then //  $p$  is a global parameter
7:       negligent  $\leftarrow$  True
8:     end if
9:   end if
10:  if  $\text{State} = \text{WAITING FOR NOTHING REVOKED} \wedge$  activation is not caused by
    output (NOTHING REVOKED), received by a member of the list of old hosts
    then // the only way for this case to be true is if the old host punished a
    misbehaving counterparty
11:     $\text{State} \leftarrow \text{BASE PUNISHED}$ 
12:  end if

13: On (INIT,  $pk_{P,\text{out}}$ ):
14:   ensure  $\text{State} = \perp$ 
15:    $\text{State} \leftarrow \text{INIT}$ 
16:    $\text{hosting} \leftarrow \text{False}$ 
17:   store  $pk_{P,\text{out}}$ 
18:    $(c_A, c_B, \text{locked}_A, \text{locked}_B) \leftarrow (0, 0, 0, 0)$ 
19:    $(\text{paid\_out}, \text{paid\_in}) \leftarrow (\emptyset, \emptyset)$ 
20:   negligent  $\leftarrow \text{False}$ 
21:    $\text{last\_poll} \leftarrow \perp$ 
22:   output (INIT OK)

23: On (TOP UP):

```

```

24:   ensure  $P = Alice$  // activated party is the funder
25:   ensure  $State = INIT$ 
26:    $(sk_{P,chain}, pk_{P,chain}) \leftarrow KEYGEN()$ 
27:   input (READ) to  $\mathcal{G}_{Ledger}$  and assign output to  $\Sigma$ 
28:   output (TOP UP TO,  $pk_{P,chain}$ )
29:   while  $\neg \exists tx \in \Sigma, c_{P,chain} : (c_{P,chain}, pk_{P,chain}) \in tx.outputs$  do
30:     // while waiting, all other messages by  $P$  are ignored
31:     wait for input (CHECK TOP UP)
32:     input (READ) to  $\mathcal{G}_{Ledger}$  and assign output to  $\Sigma$ 
33:   end while
34:    $State \leftarrow TOPPED\ UP$ 
35:   output (TOP UP OK,  $c_{P,chain}$ )

36: On (BALANCE):
37:   ensure  $State \in \{OPEN, CLOSED\}$ 
38:   output (BALANCE,  $c_A, pk_{A,out}, c_B, pk_{B,out}, locked_A, locked_B$ )

```

Fig. 24.

Process LN – methods used by VIRT

```

1: REVOKEPREVIOUS():
2:   ensure  $State \in \{WAITING\ FOR\ (OUTBOUND)\ REVOCATION\}$ 
3:    $R_{\bar{P},i} \leftarrow TX \{input: C_{P,i}.outputs.P, output: (C_{P,i}.outputs.P.value,$ 
    $pk_{\bar{P},out})\}$ 
4:    $sig_{A,R,i} \leftarrow SIGN(R_{\bar{P},i}, sk_{P,R,i})$ 
5:   if  $State = WAITING\ FOR\ REVOCATION$  then
6:      $State \leftarrow WAITING\ FOR\ INBOUND\ REVOCATION$ 
7:   else //  $State = WAITING\ FOR\ OUTBOUND\ REVOCATION$ 
8:      $i \leftarrow i + 1$ 
9:      $State \leftarrow WAITING\ FOR\ HOSTS\ READY$ 
10:  end if
11:   $host_P \leftarrow host'_P$  // forget old host, use new host instead
12:   $layer \leftarrow layer + 1$ 
13:  return  $sig_{P,R,i}$ 

14: PROCESSREMOTEREVOCATION( $sig_{\bar{P},R,i}$ ):
15:   ensure  $State = WAITING\ FOR\ (INBOUND)\ REVOCATION$ 
16:    $R_{\bar{P},i} \leftarrow TX \{input: C_{\bar{P},i}.outputs.\bar{P}, output: (C_{\bar{P},i}.outputs.\bar{P}.value,$ 
    $pk_{P,out})\}$ 
17:   ensure  $VERIFY(R_{\bar{P},i}, sig_{\bar{P},R,i}, pk_{\bar{P},R,i}) = True$ 
18:   if  $State = WAITING\ FOR\ REVOCATION$  then
19:      $State \leftarrow WAITING\ FOR\ OUTBOUND\ REVOCATION$ 
20:   else //  $State = WAITING\ FOR\ INBOUND\ REVOCATION$ 

```



```

21:      $i \leftarrow i + 1$ 
22:      $State \leftarrow \text{WAITING FOR HOSTS READY}$ 
23: end if
24: return (OK)

25: NEGLIGENT():
26:      $\text{negligent} \leftarrow \text{True}$ 
27:     return (OK)

```

Fig. 25.

Process LN.EXCHANGEOPENKEYS()

```

1:  $(sk_{A,F}, pk_{A,F}), (sk_{A,R,1}, pk_{A,R,1}), (sk_{A,R,2}, pk_{A,R,2}) \leftarrow \text{KEYGEN}()^3$ 
2:  $State \leftarrow \text{WAITING FOR OPENING KEYS}$ 
3: send (OPEN,  $c$ , hops,  $pk_{A,F}, pk_{A,R,1}, pk_{A,R,2}, pk_{A,out}$ ) to fundee
4: // colored code is run by honest fundee. Validation is implicit
5: ensure we run the code of Bob
6: ensure State = INIT
7: store  $pk_{A,F}, pk_{A,R,1}, pk_{A,R,2}, pk_{A,out}$ 
8:  $(sk_{B,F}, pk_{B,F}), (sk_{B,R,1}, pk_{B,R,1}), (sk_{B,R,2}, pk_{B,R,2}) \leftarrow \text{KEYGEN}()^3$ 
9: if hops = "ledger" then // opening base channel
10:     layer  $\leftarrow 0$ 
11:      $t_P \leftarrow s + p$  //  $s$  is the upper bound of  $\eta$  from Lemma 7.19 of [11]
12:     State  $\leftarrow \text{WAITING FOR COMM SIG}$ 
13: else // opening virtual channel
14:     State  $\leftarrow \text{WAITING FOR CHECK KEYS}$ 
15: end if
16: reply (ACCEPT CHANNEL,  $pk_{B,F}, pk_{B,R,1}, pk_{B,R,2}, pk_{B,out}$ )
17: ensure State = WAITING FOR OPENING KEYS
18: store  $pk_{B,F}, pk_{B,R,1}, pk_{B,R,2}, pk_{B,out}$ 
19:  $State \leftarrow \text{OPENING KEYS OK}$ 

```

Fig. 26.

Process LN.PREPAREBASE()

```

1: if hops = "ledger" then // opening base channel
2:      $F \leftarrow \text{TX } \{\text{input: } (c, pk_{A,chain}), \text{output: } (c, 2/\{pk_{A,F}, pk_{B,F}\})\}$ 
3:     hostP  $\leftarrow \text{"ledger"}$ 
4:     layer  $\leftarrow 0$ 
5:      $t_P \leftarrow s + p$ 

```

```

6: else // opening virtual channel
7:   input (FUND ME, Bob, hops, c,  $pk_{A,F}$ ,  $pk_{B,F}$ ) to hops[0].left and expect
   output (FUNDED, hostP, funder_layer, tP) // ignore any other message
8:   layer  $\leftarrow$  funder_layer
9: end if

```

Fig. 27.

Process LN.EXCHANGEOPENSIGS()

```

1: //  $s = (2 + q) \cdot \text{windowSize}$ , where  $q$  and windowSize are defined in
   Proposition 1
2:  $C_{A,0} \leftarrow \text{TX}$  {input: ( $c$ ,  $2/\{pk_{A,F}, pk_{B,F}\}$ ), outputs: ( $c$ , ( $pk_{A,\text{out}} + (p + s)$ )  $\vee$ 
    $2/\{pk_{A,R,1}, pk_{B,R,1}\}$ ), ( $0$ ,  $pk_{B,\text{out}}$ )}}
3:  $C_{B,0} \leftarrow \text{TX}$  {input: ( $c$ ,  $2/\{pk_{A,F}, pk_{B,F}\}$ ), outputs: ( $c$ ,  $pk_{A,\text{out}}$ ), ( $0$ ,
   ( $pk_{B,\text{out}} + (p + s)$ )  $\vee$   $2/\{pk_{A,R,1}, pk_{B,R,1}\}$ )}}
4:  $\text{sig}_{A,C,0} \leftarrow \text{SIGN}(C_{B,0}, sk_{A,F})$ 
5: State  $\leftarrow$  WAITING FOR COMM SIG
6: send (FUNDING CREATED, ( $c$ ,  $pk_{A,\text{chain}}$ ),  $\text{sig}_{A,C,0}$ ) to fundee
7: ensure State = WAITING FOR COMM SIG // if opening virtual channel, we have
   received (FUNDED, host_fundee) by hops[-1].right (Fig 30, l. 3)
8: if hops = "ledger" then // opening base channel
9:    $F \leftarrow \text{TX}$  {input: ( $c$ ,  $pk_{A,\text{chain}}$ ), output: ( $c$ ,  $2/\{pk_{A,F}, pk_{B,F}\}$ )}}
10: end if
11:  $C_{B,0} \leftarrow \text{TX}$  {input: ( $c$ ,  $2/\{pk_{A,F}, pk_{B,F}\}$ ), outputs: ( $c$ ,  $pk_{A,\text{out}}$ ), ( $0$ ,
   ( $pk_{B,\text{out}} + (p + s)$ )  $\vee$   $2/\{pk_{A,R,1}, pk_{B,R,1}\}$ )}}
12: ensure VERIFY( $C_{B,0}$ ,  $\text{sig}_{A,C,0}$ ,  $pk_{A,F}$ ) = True
13:  $C_{A,0} \leftarrow \text{TX}$  {input: ( $c$ ,  $2/\{pk_{A,F}, pk_{B,F}\}$ ), outputs: ( $c$ , ( $pk_{A,\text{out}} + (p + s)$ )  $\vee$ 
    $2/\{pk_{A,R,1}, pk_{B,R,1}\}$ ), ( $0$ ,  $pk_{B,\text{out}}$ )}}
14:  $\text{sig}_{B,C,0} \leftarrow \text{SIGN}(C_{A,0}, sk_{B,F})$ 
15: if hops = "ledger" then // opening base channel
16:   State  $\leftarrow$  WAITING TO CHECK FUNDING
17: else // opening virtual channel
18:    $c_A \leftarrow c$ ;  $c_B \leftarrow 0$ ;  $i \leftarrow 0$ 
19:   State  $\leftarrow$  OPEN
20: end if
21: reply (FUNDING SIGNED,  $\text{sig}_{B,C,0}$ )
22: ensure State = WAITING FOR COMM SIG
23: ensure VERIFY( $C_{A,0}$ ,  $\text{sig}_{B,C,0}$ ,  $pk_{B,F}$ ) = True

```

Fig. 28.

Process LN.COMMITBASE()

```

1:  $\text{sig}_F \leftarrow \text{SIGN}(F, sk_{A,\text{chain}})$ 
2: input (SUBMIT,  $(F, \text{sig}_F)$ ) to  $\mathcal{G}_{\text{Ledger}}$  // enter “while” below before sending
3: while  $F \notin \Sigma$  do
4:   wait for input (CHECK FUNDING) // ignore all other messages
5:   input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
6: end while

```

Fig. 29.

Process LN – external open messages for Bob

```

1: On output (FUNDED,  $\text{host}_P$ ,  $\text{funder\_layer}$ ,  $t_P$ ) by  $\text{hops}[-1].\text{right}$ :
2:   ensure  $\text{State} = \text{WAITING FOR FUNDED}$ 
3:   store  $\text{host}_P$  // we will talk directly to  $\text{host}_P$ 
4:    $\text{layer} \leftarrow \text{funder\_layer}$ 
5:    $\text{State} \leftarrow \text{WAITING FOR COMM SIG}$ 
6:   reply (FUND ACK)

7: On output (CHECK KEYS,  $(pk_1, pk_2)$ ) by  $\text{hops}[-1].\text{right}$ :
8:   ensure  $\text{State} = \text{WAITING FOR CHECK KEYS}$ 
9:   ensure  $pk_1 = pk_{A,F} \wedge pk_2 = pk_{B,F}$ 
10:   $\text{State} \leftarrow \text{WAITING FOR FUNDED}$ 
11:  reply (KEYS OK)

12: On input (CHECK FUNDING):
13:  ensure  $\text{State} = \text{WAITING TO CHECK FUNDING}$ 
14:  input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
15:  if  $F \in \Sigma$  then
16:     $\text{State} \leftarrow \text{OPEN}$ 
17:    reply (OPEN OK)
18:  end if

```

Fig. 30.

Process LN – On (OPEN, c , hops, fundee):

```

1: // fundee is Bob
2: ensure we run the code of Alice // activated party is the funder
3: if hops = “ledger” then // opening base channel
4:   ensure  $\text{State} = \text{TOPPED UP}$ 
5:   ensure  $c = c_{A,\text{chain}}$ 

```

```

6: else // opening virtual channel
7:   ensure  $\text{len}(\text{hops}) \geq 2$  // cannot open a virtual over 1 channel
8: end if
9: LN.EXCHANGEOPENKEYS()
10: LN.PREPAREBASE()
11: LN.EXCHANGEOPENSIGS()
12: if  $\text{hops} = \text{"ledger"}$  then
13:   LN.COMMITBASE()
14: end if
15: input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
16:  $\text{last\_poll} \leftarrow |\Sigma|$ 
17:  $c_A \leftarrow c$ ;  $c_B \leftarrow 0$ ;  $i \leftarrow 0$ 
18:  $\text{State} \leftarrow \text{OPEN}$ 
19: output (OPEN OK,  $c$ , fundee, hops)

```

Fig. 31.

Process LN.UPDATEFORVIRTUAL()

```

1:  $C_{\bar{P},i+1} \leftarrow C_{\bar{P},i}$  with  $pk'_{P,F}$ ,  $pk'_{\bar{P},F}$ ,  $pk_{\bar{P},R,i+1}$  and  $pk_{P,R,i+1}$  instead of  $pk_{P,F}$ ,
    $pk_{\bar{P},F}$ ,  $pk_{\bar{P},R,i}$  and  $pk_{P,R,i}$  respectively, reducing the input and  $P$ 's output by
    $c_{\text{virt}}$ 
2:  $\text{sig}_{P,C,i+1} \leftarrow \text{SIGN}(C_{\bar{P},i+1})$  // kept by  $\bar{P}$ 
3:  $(sk_{P,R,i+2}, pk_{P,R,i+2}) \leftarrow \text{KEYGEN}()$ 
4: send (UPDATE FORWARD,  $\text{sig}_{P,C,i+1}$ ,  $pk_{P,R,i+2}$ ) to  $\bar{P}$ 
5: //  $P$  refers to payer and  $\bar{P}$  to payee both in local and remote code
6:  $C_{\bar{P},i+1} \leftarrow C_{\bar{P},i}$  with  $pk'_{P,F}$ ,  $pk'_{\bar{P},F}$ ,  $pk_{P,R,i+1}$  and  $pk_{\bar{P},R,i+1}$  instead of  $pk_{P,F}$ ,
    $pk_{\bar{P},F}$ ,  $pk_{P,R,i}$  and  $pk_{\bar{P},R,i}$  respectively, reducing the input and  $P$ 's output by
    $c_{\text{virt}}$ 
7: ensure  $\text{VERIFY}(C_{\bar{P},i+1}, \text{sig}_{P,C,i+1}, pk'_{P,F}) = \text{True}$ 
8:  $C_{P,i+1} \leftarrow C_{P,i}$  with  $pk'_{\bar{P},F}$ ,  $pk'_{P,F}$ ,  $pk_{\bar{P},R,i+1}$  and  $pk_{P,R,i+1}$  instead of  $pk_{\bar{P},F}$ ,
    $pk_{P,F}$ ,  $pk_{\bar{P},R,i}$  and  $pk_{P,R,i}$  respectively, reducing the input and  $P$ 's output by
    $c_{\text{virt}}$ 
9:  $\text{sig}_{\bar{P},C,i+1} \leftarrow \text{SIGN}(C_{P,i+1}, sk'_{\bar{P},F})$  // kept by  $P$ 
10:  $(sk_{\bar{P},R,i+2}, pk_{\bar{P},R,i+2}) \leftarrow \text{KEYGEN}()$ 
11: reply (UPDATE BACK,  $\text{sig}_{\bar{P},C,i+1}$ ,  $pk_{\bar{P},R,i+2}$ )
12:  $C_{P,i+1} \leftarrow C_{P,i}$  with  $pk'_{\bar{P},F}$ ,  $pk'_{P,F}$ ,  $pk_{\bar{P},R,i+1}$  and  $pk_{P,R,i+1}$  instead of  $pk_{\bar{P},F}$ ,
    $pk_{P,F}$ ,  $pk_{\bar{P},R,i}$  and  $pk_{P,R,i}$  respectively, reducing the input and  $P$ 's output by
    $c_{\text{virt}}$ 
13: ensure  $\text{VERIFY}(C_{P,i+1}, \text{sig}_{\bar{P},C,i+1}, pk'_{\bar{P},F}) = \text{True}$ 

```

Fig. 32.

Process LN – virtualise start and end

- 1: On input (FUND ME, **fundee**, **hops**, c_{virt} , $pk_{A,V}$, $pk_{B,V}$) by **funder**:
- 2: ensure $State = \text{OPEN}$
- 3: ensure $c_P - \text{locked}_P \geq c_{\text{virt}}$
- 4: $State \leftarrow \text{VIRTUALISING}$
- 5: $(sk'_{P,F}, pk'_{P,F}) \leftarrow \text{KEYGEN}()$
- 6: define new VIRT ITI host'_P
- 7: send (VIRTUALISING, host'_P , $pk'_{P,F}$, **hops**, **fundee**, c_{virt} , 2, $\text{len}(\text{hops})$) to \bar{P}
and expect reply (VIRTUALISING ACK, $\text{host}'_{\bar{P}}$, $pk'_{\bar{P},F}$)
- 8: ensure $pk'_{\bar{P},F}$ is different from $pk_{\bar{P},F}$ and all older \bar{P} 's funding public keys
- 9: LN.UPDATEFORVIRTUAL()
- 10: $State \leftarrow \text{WAITING FOR REVOCATION}$
- 11: input (HOST ME, **funder**, **fundee**, $\text{host}'_{\bar{P}}$, host_P , c_P , $c_{\bar{P}}$, c_{virt} , $pk_{A,V}$, $pk_{B,V}$,
 $(sk'_{P,F}, pk'_{P,F})$, $(sk_{P,F}, pk_{P,F})$, $pk_{\bar{P},F}$, $pk'_{\bar{P},F}$, $pk_{P,\text{out}}$, $\text{len}(\text{hops})$) to host'_P
- 12: On output (HOSTS READY, t_P) by host_P : // host_P is the new host, renamed
in Fig. 25, l. 12
- 13: ensure $State = \text{WAITING FOR HOSTS READY}$
- 14: $State \leftarrow \text{OPEN}$
- 15: **hosting** $\leftarrow \text{True}$
- 16: move $sk_{P,F}$, $pk_{P,F}$, $pk_{\bar{P},F}$ to list of old funding keys
- 17: $(sk_{P,F}, pk_{P,F}) \leftarrow (sk'_{P,F}, pk'_{P,F})$; $pk_{\bar{P},F} \leftarrow pk'_{\bar{P},F}$
- 18: **if** $\text{len}(\text{hops}) = 1$ **then** // we are the last hop
- 19: output (FUNDED, host_P , **layer**, t_P) to **fundee** and expect reply (FUND
ACK)
- 20: **else if** we have received input FUND ME just before we moved to the
VIRTUALISING state **then** // we are the first hop
- 21: $c_P \leftarrow c_P - c_{\text{virt}}$
- 22: output (FUNDED, host_P , **layer**, t_P) to **funder** // do not expect reply
by **funder**
- 23: **end if**
- 24: reply (HOST ACK)

Fig. 33.

Process LN – virtualise hops

- 1: On (VIRTUALISING, $\text{host}'_{\bar{P}}$, $pk'_{\bar{P},F}$, **hops**, **fundee**, c_{virt} , i , n) by \bar{P} :
- 2: ensure $State = \text{OPEN}$
- 3: ensure $c_{\bar{P}} - \text{locked}_{\bar{P}} \geq c_{\text{virt}}$; $1 \leq i \leq n$
- 4: ensure $pk'_{\bar{P},F}$ is different from $pk_{\bar{P},F}$ and all older \bar{P} 's funding public keys
- 5: $State \leftarrow \text{VIRTUALISING}$
- 6: $\text{locked}_{\bar{P}} \leftarrow \text{locked}_{\bar{P}} + c_{\text{virt}}$ // if \bar{P} is hosting the funder, \bar{P} will transfer
 c_{virt} coins instead of locking them, but the end result is the same

```

7:    $(sk'_{P,F}, pk'_{P,F}) \leftarrow \text{KEYGEN}()$ 
8:   if  $\text{len}(\text{hops}) > 1$  then // we are not the last hop
9:     define new VIRT ITI  $\text{host}'_P$ 
10:    input (VIRTUALISING,  $\text{host}'_P$ ,  $(sk'_{P,F}, pk'_{P,F})$ ,  $pk'_{\bar{P},F}$ ,  $pk_{P,\text{out}}$ ,  $\text{hops}[1:]$ ,
    fundee,  $c_{\text{virt}}$ ,  $c_{\bar{P}}$ ,  $c_P$ ,  $i$ ,  $n$ ) to  $\text{hops}[1].\text{left}$  and expect reply (VIRTUALISING
    ACK,  $\text{host\_sibling}$ ,  $pk_{\text{sib},\bar{P},F}$ )
11:    input (INIT,  $\text{host}_P$ ,  $\text{host}'_{\bar{P}}$ ,  $\text{host\_sibling}$ ,  $(sk'_{P,F}, pk'_{P,F})$ ,  $pk'_{\bar{P},F}$ ,
     $pk_{\text{sib},\bar{P},F}$ ,  $(sk_{P,F}, pk_{P,F})$ ,  $pk_{\bar{P},F}$ ,  $pk_{P,\text{out}}$ ,  $c_P$ ,  $c_{\bar{P}}$ ,  $c_{\text{virt}}$ ,  $t_P$ ,  $i$ , "left",  $n$ ) to  $\text{host}'_P$ 
    and expect reply (HOST INIT OK)
12:    else // we are the last hop
13:      input (INIT,  $\text{host}_P$ ,  $\text{host}'_{\bar{P}}$ , fundee=fundee,  $(sk'_{P,F}, pk'_{P,F})$ ,  $pk'_{\bar{P},F}$ ,
     $(sk_{P,F}, pk_{P,F})$ ,  $pk_{\bar{P},F}$ ,  $pk_{P,\text{out}}$ ,  $c_P$ ,  $c_{\bar{P}}$ ,  $c_{\text{virt}}$ ,  $t_P$ ,  $i$ , "left",  $n$ ) to new VIRT ITI
     $\text{host}'_P$  and expect reply (HOST INIT OK)
14:    end if
15:     $\text{State} \leftarrow \text{WAITING FOR REVOCATION}$ 
16:    send (VIRTUALISING ACK,  $\text{host}'_P$ ,  $pk'_{P,F}$ ) to  $\bar{P}$ 

17: On input (VIRTUALISING,  $\text{host\_sibling}$ ,  $(sk'_{P,F}, pk'_{P,F})$ ,  $pk_{\text{sib},\bar{P},F}$ ,  $pk_{\text{sib},\text{out}}$ ,
    hops, fundee,  $c_{\text{virt}}$ ,  $c_{\text{sib},\text{rem}}$ ,  $c_{\text{sib}}$ ,  $i$ ,  $n$ ) by sibling:
18:   ensure  $\text{State} = \text{OPEN}$ 
19:   ensure  $c_P - \text{locked}_P \geq c_{\text{virt}}$ 
20:   ensure  $c_{\text{sib},\text{rem}} \geq c_P \wedge c_{\bar{P}} \geq c_{\text{sib}}$  // avoid value loss by griefing attack: one
    counterparty closes with old version, the other stays idle forever
21:    $\text{State} \leftarrow \text{VIRTUALISING}$ 
22:    $\text{locked}_P \leftarrow \text{locked}_P + c_{\text{virt}}$ 
23:   define new VIRT ITI  $\text{host}'_P$ 
24:   send (VIRTUALISING,  $\text{host}'_P$ ,  $pk'_{P,F}$ , hops, fundee,  $c_{\text{virt}}$ ,  $i+1$ ,  $n$ ) to
    hops[0].right and expect reply (VIRTUALISING ACK,  $\text{host}'_{\bar{P}}$ ,  $pk'_{\bar{P},F}$ )
25:   ensure  $pk'_{\bar{P},F}$  is different from  $pk_{\bar{P},F}$  and all older  $\bar{P}$ 's funding public keys
26:   LN.UPDATEFORVIRTUAL()
27:   input (INIT,  $\text{host}_P$ ,  $\text{host}'_{\bar{P}}$ ,  $\text{host\_sibling}$ ,  $(sk'_{P,F}, pk'_{P,F})$ ,  $pk'_{\bar{P},F}$ ,  $pk_{\text{sib},\bar{P},F}$ ,
     $(sk_{P,F}, pk_{P,F})$ ,  $pk_{\bar{P},F}$ ,  $pk_{\text{sib},\text{out}}$ ,  $c_P$ ,  $c_{\bar{P}}$ ,  $c_{\text{virt}}$ ,  $i$ , "right",  $n$ ) to  $\text{host}'_P$  and expect
    reply (HOST INIT OK)
28:    $\text{State} \leftarrow \text{WAITING FOR REVOCATION}$ 
29:   output (VIRTUALISING ACK,  $\text{host}'_P$ ,  $pk'_{P,F}$ ) to sibling

```

Fig. 34.

Process LN.SIGNATURESROUNDTRIP()

- 1: $C_{\bar{P},i+1} \leftarrow C_{\bar{P},i}$ with $pk_{P,R,i+1}$ and $pk_{\bar{P},R,i+1}$ instead of $pk_{P,R,i}$ and $pk_{\bar{P},R,i}$ respectively, and x coins moved from P 's to \bar{P} 's output
- 2: $\text{sig}_{P,C,i+1} \leftarrow \text{SIGN}(C_{\bar{P},i+1}, sk_{P,F})$ // kept by \bar{P}
- 3: $(sk_{P,R,i+2}, pk_{P,R,i+2}) \leftarrow \text{KEYGEN}()$

```

4:  $State \leftarrow$  WAITING FOR COMMITMENT SIGNED
5: send (PAY,  $x$ ,  $\text{sig}_{P,C,i+1}$ ,  $pk_{P,R,i+2}$ ) to  $\bar{P}$ 
6: //  $P$  refers to payer and  $\bar{P}$  to payee both in local and remote code
7: ensure  $State =$  WAITING TO GET PAID  $\wedge x = y$ 
8:  $C_{\bar{P},i+1} \leftarrow C_{\bar{P},i}$  with  $pk_{P,R,i+1}$  and  $pk_{\bar{P},R,i+1}$  instead of  $pk_{P,R,i}$  and  $pk_{\bar{P},R,i}$  respectively, and  $x$  coins moved from  $P$ 's to  $\bar{P}$ 's output
9: ensure  $\text{VERIFY}(C_{\bar{P},i+1}, \text{sig}_{P,C,i+1}, pk_{P,F}) = \text{True}$ 
10:  $C_{P,i+1} \leftarrow C_{P,i}$  with  $pk_{\bar{P},R,i+1}$  and  $pk_{P,R,i+1}$  instead of  $pk_{\bar{P},R,i}$  and  $pk_{P,R,i}$  respectively, and  $x$  coins moved from  $P$ 's to  $\bar{P}$ 's output
11:  $\text{sig}_{\bar{P},C,i+1} \leftarrow \text{SIGN}(C_{P,i+1}, sk_{\bar{P},F})$  // kept by  $P$ 
12:  $R_{P,i} \leftarrow \text{TX}$  {input:  $C_{\bar{P},i}.\text{outputs}.\bar{P}$ , output: ( $c_{\bar{P}}$ ,  $pk_{P,\text{out}}$ )}
13:  $\text{sig}_{\bar{P},R,i} \leftarrow \text{SIGN}(R_{P,i}, sk_{\bar{P},R,i})$ 
14:  $(sk_{\bar{P},R,i+2}, pk_{\bar{P},R,i+2}) \leftarrow \text{KEYGEN}()$ 
15:  $State \leftarrow$  WAITING FOR PAY REVOCATION
16: reply (COMMITMENT SIGNED,  $\text{sig}_{\bar{P},C,i+1}$ ,  $\text{sig}_{\bar{P},R,i}$ ,  $pk_{\bar{P},R,i+2}$ )
17: ensure  $State =$  WAITING FOR COMMITMENT SIGNED
18:  $C_{P,i+1} \leftarrow C_{P,i}$  with  $pk_{\bar{P},R,i+1}$  and  $pk_{P,R,i+1}$  instead of  $pk_{\bar{P},R,i}$  and  $pk_{P,R,i}$  respectively, and  $x$  coins moved from  $P$ 's to  $\bar{P}$ 's output

```

Fig. 35.

Process LN.REVOCATIONS_{TRIP}()

```

1: ensure  $\text{VERIFY}(C_{P,i+1}, \text{sig}_{\bar{P},C,i+1}, pk_{\bar{P},F}) = \text{True}$ 
2:  $R_{P,i} \leftarrow \text{TX}$  {input:  $C_{\bar{P},i}.\text{outputs}.\bar{P}$ , output: ( $c_{\bar{P}}$ ,  $pk_{P,\text{out}}$ )}
3: ensure  $\text{VERIFY}(R_{P,i}, \text{sig}_{\bar{P},R,i}, pk_{\bar{P},R,i}) = \text{True}$ 
4:  $R_{\bar{P},i} \leftarrow \text{TX}$  {input:  $C_{P,i}.\text{outputs}.P$ , output: ( $c_P$ ,  $pk_{\bar{P},\text{out}}$ )}
5:  $\text{sig}_{P,R,i} \leftarrow \text{SIGN}(R_{\bar{P},i}, sk_{P,R,i})$ 
6: add  $x$  to paid_out
7:  $c_P \leftarrow c_P - x$ ;  $c_{\bar{P}} \leftarrow c_{\bar{P}} + x$ ;  $i \leftarrow i + 1$ 
8:  $State \leftarrow$  OPEN
9: if  $\text{host}_P \neq \text{"ledger"}$   $\wedge$  we have a host_sibling then // we are intermediary channel
10:   input (NEW BALANCE,  $c_P$ ,  $c_{\bar{P}}$ ) to  $\text{host}_P$ 
11:   relay message as input to sibling // run by VIRT
12:   relay message as output to guest // run by VIRT
13:   store new sibling balance and reply (NEW BALANCE OK)
14:   output (NEW BALANCE OK) to sibling // run by VIRT
15:   output (NEW BALANCE OK) to guest // run by VIRT
16: end if
17: send (REVOKE AND ACK,  $\text{sig}_{P,R,i}$ ) to  $\bar{P}$ 
18: ensure  $State =$  WAITING FOR PAY REVOCATION
19:  $R_{\bar{P},i} \leftarrow \text{TX}$  {input:  $C_{P,i}.\text{outputs}.P$ , output: ( $c_P$ ,  $pk_{\bar{P},\text{out}}$ )}
20: ensure  $\text{VERIFY}(R_{\bar{P},i}, \text{sig}_{P,R,i}, pk_{P,R,i}) = \text{True}$ 
21: add  $x$  to paid_in

```

```

22:  $c_P \leftarrow c_P - x; c_{\bar{P}} \leftarrow c_{\bar{P}} + x; i \leftarrow i + 1$ 
23:  $State \leftarrow \text{OPEN}$ 
24: if  $\text{host}_P \neq \text{"ledger"} \wedge \bar{P}$  has a  $\text{host\_sibling}$  then // we are intermediary
    channel
25:   input (NEW BALANCE,  $c_{\bar{P}}, c_P$ ) to  $\text{host}_{\bar{P}}$ 
26:   relay message as input to  $\text{sibling}$  // run by VIRT
27:   relay message as output to  $\text{guest}$  // run by VIRT
28:   store new sibling balance and reply (NEW BALANCE OK)
29:   output (NEW BALANCE OK) to  $\text{sibling}$  // run by VIRT
30:   output (NEW BALANCE OK) to  $\text{guest}$  // run by VIRT
31: end if

```

Fig. 36.

Process LN – On (PAY, x):

```

1: ensure  $State = \text{OPEN} \wedge c_P \geq x$ 
2: if  $\text{host}_P \neq \text{"ledger"} \wedge P$  has a  $\text{host\_sibling}$  then // we are intermediary
    channel
3:   ensure  $c_{\text{sib,rem}} \geq c_P - x \wedge c_{\bar{P}} + x \geq c_{\text{sib}}$  // avoid value loss by griefing
    attack: one counterparty closes with old version, the other stays idle forever
4: end if
5: LN.SIGNATURESROUNDTRIP()
6: LN.REVOCATIONSTRIP()
7: // No output is given to the caller, this is intentional

```

Fig. 37.

Process LN – On (GET PAID, y):

```

1: ensure  $State = \text{OPEN} \wedge c_{\bar{P}} \geq y$ 
2: if  $\text{host}_P \neq \text{"ledger"} \wedge P$  has a  $\text{host\_sibling}$  then // we are intermediary
    channel
3:   ensure  $c_P + y \leq c_{\text{sib,rem}} \wedge c_{\text{sib}} \leq c_{\bar{P}} - y$  // avoid value loss by griefing attack
4: end if
5: store  $y$ 
6:  $State \leftarrow \text{WAITING TO GET PAID}$ 

```

Fig. 38.

Process LN – On (CHECK FOR LATERAL CLOSE):

```

1: if  $\text{host}_P \neq \text{"ledger"}$  then
2:   input (CHECK FOR LATERAL CLOSE) to  $\text{host}_P$ 
3: end if

```

Fig. 39.

Process LN – On (CHECK CHAIN FOR CLOSED):

```

1: ensure  $\text{State} \notin \{\perp, \text{INIT}, \text{TOPPED UP}\}$  // channel open
2: // even virtual channels check  $\mathcal{G}_{\text{Ledger}}$  directly. This is intentional
3: input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign reply to  $\Sigma$ 
4:  $\text{last\_poll} \leftarrow |\Sigma|$ 
5: if  $\exists 0 \leq j < i : C_{\bar{P},j} \in \Sigma$  then // counterparty has closed maliciously
6:    $\text{State} \leftarrow \text{CLOSING}$ 
7:    $\text{LN.SUBMITANDCHECKREVOCATION}(j)$ 
8:    $\text{State} \leftarrow \text{CLOSED}$ 
9:   output (CLOSED)
10: else if  $C_{P,i} \in \Sigma \vee C_{\bar{P},i} \in \Sigma$  then
11:    $\text{State} \leftarrow \text{CLOSED}$ 
12:   output (CLOSED)
13: else
14:    $\text{state\_before\_checking\_revoked} \leftarrow \text{State}$ 
15:   for each  $\text{host}$  in list of old hosts do
16:      $\text{State} \leftarrow \text{WAITING FOR NOTHING REVOKED}$ 
17:     input (CHECK FOR REVOKED) to  $\text{host}$  and expect output (NOTHING REVOKED)
18:      $\text{State} \leftarrow \text{state\_before\_checking\_revoked}$ 
19:   end for
20: end if

```

Fig. 40.

Process LN.SUBMITANDCHECKREVOCATION(j)

```

1:  $\text{sig}_{P,R,j} \leftarrow \text{SIGN}(R_{P,j}, \text{sk}_{P,R,j})$ 
2: input (SUBMIT,  $(R_{P,j}, \text{sig}_{P,R,j}, \text{sig}_{\bar{P},R,j})$ ) to  $\mathcal{G}_{\text{Ledger}}$ 
3: while  $\neg \exists R_{P,j} \in \Sigma$  do
4:   wait for input (CHECK REVOCATION) // ignore other messages
5:   input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
6: end while
7:  $c_P \leftarrow c_P + c_{\bar{P}}$ 
8: if  $\text{host}_P \neq \text{"ledger"}$  then

```

```

9:   input (USED REVOCATION) to hostP
10: end if

```

Fig. 41.

Process LN – On (FORCECLOSE):

```

1: ensure  $State \notin \{\perp, \text{INIT}, \text{TOPPED UP}, \text{CLOSED}, \text{BASE PUNISHED}\}$  // channel open
2: if hostP  $\neq$  "ledger" then // we have a virtual channel
3:    $State \leftarrow \text{HOST CLOSING}$ 
4:   input (FORCECLOSE) to hostP and keep relaying any (CHECK IF CLOSING)
   or (FORCECLOSE) input to hostP until receiving output (CLOSED) by hostP
5:   hostP  $\leftarrow$  "ledger"
6: end if
7:  $State \leftarrow \text{CLOSING}$ 
8: input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
9: if  $C_{\bar{P},i} \in \Sigma$  then // counterparty has closed honestly
10:  no-op // do nothing
11: else if  $\exists 0 \leq j < i : C_{\bar{P},j} \in \Sigma$  then // counterparty has closed maliciously
12:  LN.SUBMITANDCHECKREVOCATION( $j$ )
13: else // counterparty is idle
14:  while  $\neg \exists$  unspent output  $\in \Sigma$  that  $C_{P,i}$  can spend do // possibly due to
   an active timelock
15:    wait for input (CHECK VIRTUAL) // ignore other messages
16:    input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
17:  end while
18:   $\text{sig}'_{P,C,i} \leftarrow \text{SIGN}(C_{P,i}, sk_{P,F})$ 
19:  input (SUBMIT,  $(C_{P,i}, \text{sig}_{P,C,i}, \text{sig}'_{P,C,i})$ ) to  $\mathcal{G}_{\text{Ledger}}$ 
20: end if

```

Fig. 42.

Process LN – On output (ENABLER USED REVOCATION) by **host_P:**

```

1:  $State \leftarrow \text{BASE PUNISHED}$ 

```

Fig. 43.

Process LN – On (COOPCLOSE):

```

// any endpoint or intermediary can initiate virtual channel closing
1: ensure  $\text{host}_P \neq \text{"ledger"}$ 
2: ensure  $\text{State} = \text{OPEN}$ 
3:  $\text{we\_are\_close\_initiator} \leftarrow \text{True}$ 
4: if  $\text{hosting} = \text{True} \vee$  we have received OPEN from  $\mathcal{E}$  while  $\text{State}$  was TOPPED
   UP then // we are not the fundee of a channel that is not the base of any
   other channel
5:   if  $\text{hosting} = \text{True}$  then // we are not the funder of the channel to be
   closed
6:     the next time we are activated, if we are not activated by output
     (CHECK COOP CLOSE, ...) from  $\text{host}_P$ , set  $\text{we\_are\_close\_initiator} \leftarrow \text{False}$ 
7:   else // we are the funder of the channel to be closed
8:     the next time we are activated, if we are not activated by output (COOP
     CLOSE, ...) from  $\bar{P}$ , set  $\text{we\_are\_close\_initiator} \leftarrow \text{False}$ 
9:   end if
10:  send (COOP CLOSE) to fundee
11: else // we are the fundee of a channel that is not the base of any other
   channel
12:  the next time we are activated, if we are not activated by output (CHECK
   COOP CLOSE FUNDEE, ...) from  $\text{host}_P$ , set  $\text{we\_are\_close\_initiator} \leftarrow \text{False}$ 
13:   $\text{close\_initiator} \leftarrow P$ 
14:  execute code of Fig. 46
15: end if

```

Fig. 44.

Process LN – On (COOPCLOSED) by R :

```

1: if  $\text{hosting} = \text{True}$  then // we are intermediary
2:   ensure  $\text{State} = \text{OPEN}$ 
3: else // we are endpoint
4:   ensure  $\text{State} = \text{COOP CLOSED}$ 
5: end if
6: ensure  $\text{we\_are\_close\_initiator} = \text{True}$ 
7: ensure that the last cooperatively closed channel in which we acted as a base
   had  $R$  as its fundee
8:  $\text{we\_are\_close\_initiator} \leftarrow \text{False}$ 
9: output (COOPCLOSED)

```

Fig. 45.

Process LN – On (COOP CLOSE) by R :

// also executed when we are instructed to close a channel cooperatively by \mathcal{E} – c.f. Fig. 44, l. 14

- 1: ensure we are **fundee**
- 2: ensure **hosting** \neq True
- 3: ensure $State = \text{OPEN}$
- 4: $State \leftarrow \text{COOP CLOSING}$
- 5: $close_initiator \leftarrow R$
- 6: $sig_bal \leftarrow ((c_{\bar{P}}, c_P), \text{SIGN}((c_{\bar{P}}, c_P), sk_{P,F}))$
- 7: $State \leftarrow \text{WAITING TO REVOKE VIRT COMM}$
- 8: send (COOP CLOSE, sig_bal) to \bar{P}

Fig. 46.

Process LN – On (COOP CLOSE, $sig_bal_{\bar{P}}$) by \bar{P} :

- 1: ensure we are **funder**
- 2: ensure $State = \text{OPEN}$
- 3: parse $sig_bal_{\bar{P}}$ as $((c'_1, c'_2), sig_{\bar{P}})$
- 4: ensure $c_P = c'_1 \wedge c_{\bar{P}} = c'_2 \wedge \text{VERIFY}((c'_1, c'_2), sig_{\bar{P}}, pk_{\bar{P},F}) = \text{True}$
- 5: $sig_bal \leftarrow ((c_P, c_{\bar{P}}), \text{SIGN}((c_P, c_{\bar{P}}), sk_{P,F}), sig_{\bar{P}})$
- 6: $State \leftarrow \text{COOP CLOSING}$
- 7: input (COOP CLOSE, sig_bal) to $host_P$
- 8: ensure $State = \text{OPEN}$ // executed by $host_P$
- 9: $State \leftarrow \text{COOP CLOSING}$
- 10: output (COOP CLOSE SIGN COMM FUNDER, (c'_1, c'_2)) to $guest$
- 11: ensure $State = \text{OPEN}$ // executed by $guest$ of $host_P$
- 12: $State \leftarrow \text{COOP CLOSING}$
- 13: remove most recent keys from list of old funding keys and assign them to $sk'_{P,F}, pk'_{P,F}, pk'_{\bar{P},F}$
- 14: $C_{\bar{P},i+1} \leftarrow \text{TX}$ {input: $(c_P + c_{\bar{P}} + c'_1 + c'_2, 2/\{pk'_{P,F}, pk'_{\bar{P},F}\})$, outputs: $(c_P + c'_1, pk_{P,out}), (c_{\bar{P}} + c'_2, (pk_{\bar{P},out} + (p + s)) \vee 2/\{pk_{P,R,i+1}, pk_{\bar{P},R,i+1}\})$ }
- 15: $sig_{P,C,i+1} \leftarrow \text{SIGN}(C_{\bar{P},i+1}, sk'_{P,F})$
- 16: $(sk_{P,R,i+2}, pk_{P,R,i+2}) \leftarrow \text{KEYGEN}()$
- 17: input (NEW COMM TX, $sig_{P,C,i+1}, pk_{P,R,i+2}$) to $host_P$
- 18: rename received signature to $sig_{1,right,C}$ // executed by $host_P$
- 19: rename received public key to $pk_{1,right,R}$
- 20: send (COOP CLOSE, $sig_bal, sig_{1,right,C}, pk_{1,right,R}$) to \bar{P} and expect reply (COOP CLOSE BACK, ($right_comms_revkeys, right_revocations$))
- 21: $R_{loc,virt} \leftarrow \text{TX}$ {input: $(c_{virt}, 2/\{pk_{1,rev}, pk_{2,rev}\})$, output: $(c_{virt}, pk_{1,out})$ }
- 22: extract $sig_{2,right,rev,virt}$ from $right_revocations$
- 23: ensure $\text{VERIFY}(R_{loc,virt}, sig_{2,right,rev,virt}, pk_{2,rev}) = \text{True}$
- 24: $R_{loc,fund} \leftarrow \text{TX}$ {input: $(c_P + c_{\bar{P}}, 2/\{pk_{1,rev}, pk_{2,rev}\})$, output: $(c_P + c_{\bar{P}}, pk_{1,out})$ }
- 25: extract $sig_{2,right,rev,fund}$ from $right_revocations$

```

26: ensure VERIFY( $R_{\text{loc},\text{fund}}$ ,  $\text{sig}_{2,\text{right},\text{rev},\text{fund}}$ ,  $pk_{2,\text{rev}}$ ) = True
27: extract  $\text{sig}_{2,\text{right},R}$  from right_revocations
28: extract  $\text{sig}_{2,\text{right},C}$  from right_comms_revkeys
29: extract  $pk_{2,R}$  from right_comms_revkeys
30: output (VERIFY REVOKE,  $\text{sig}_{2,\text{right},C}$ ,  $\text{sig}_{2,\text{right},R}$ ,  $pk_{2,R}$ , hostP) to guest
31: store  $\text{sig}_{2,\text{right},C}$  as  $\text{sig}_{\bar{P},C,i+1}$  // executed by guest of hostP
32: store  $\text{sig}_{2,\text{right},R}$  as  $\text{sig}_{\bar{P},R,i}$ 
33: store received public key as  $pk_{\bar{P},R,i+2}$ 
34:  $C_{P,i+1} \leftarrow \text{TX}$  {input: ( $c_P + c_{\bar{P}} + c'_1 + c'_2$ ), outputs:
    ( $c_P + c'_1$ , ( $pk_{P,\text{out}} + (p + s)$ )  $\vee 2/\{pk_{P,R,i+1}, pk_{\bar{P},R,i+1}\}$ ), ( $c_{\bar{P}} + c'_2, pk_{\bar{P},\text{out}}$ )}}
35: ensure VERIFY( $C_{P,i+1}$ ,  $\text{sig}_{\bar{P},C,i+1}$ ,  $pk_{\bar{P},F}$ ) = True
36:  $R_{P,i} \leftarrow \text{TX}$  {input:  $C_{\bar{P},i}.\text{outputs}.\bar{P}$ , output: ( $c_{\bar{P}}, pk_{P,\text{out}}$ )}}
37: ensure VERIFY( $R_{P,i}$ ,  $\text{sig}_{\bar{P},R,i}$ ,  $pk_{\bar{P},R,i}$ ) = True
38: input (VERIFIED) to hostP
39: extract  $\text{sig}_{n,\text{left},R}$  from right_revocations // executed by hostP
40: output (VERIFY REVOCATION,  $\text{sig}_{n,\text{left},R}$ ) to funder
41:  $R_{P,i} \leftarrow \text{TX}$  {input:  $C_{\bar{P},i}.\text{outputs}.\bar{P}$ , output: ( $c_{\bar{P}}, pk_{P,\text{out}}$ )}}
42: ensure VERIFY( $R_{P,i}$ ,  $\text{sig}_{\bar{P},R,i}$ ,  $pk_{\bar{P},R,i}$ ) = True
43:  $R_{\bar{P},i} \leftarrow \text{TX}$  {input:  $C_{P,i}.\text{outputs}.P$ , output: ( $c_P, pk_{\bar{P},\text{out}}$ )}}
44:  $\text{sig}_{P,R,i} \leftarrow \text{SIGN}(R_{\bar{P},i}, sk_{P,R,i})$ 
45:  $State \leftarrow \text{COOP CLOSED}$  // in LN, only virtual channels can end up in this state
46: input (COOP CLOSE REVOCATION,  $\text{sig}_{P,R,i}$ ) to hostP
47: output (COOP CLOSE REVOCATIONS, hostP) to guest // executed by hostP
48:  $R_{\bar{P},i} \leftarrow \text{TX}$  {input:  $C_{P,i}.\text{outputs}.P$ , output: ( $c_P, pk_{\bar{P},\text{out}}$ )}} // executed by
    guest of hostP
49:  $\text{sig}_{P,R,i} \leftarrow \text{SIGN}(R_{\bar{P},i}, sk_{P,R,i})$ 
50: add  $sk_{P,F}, pk_{P,F}, pk_{\bar{P},F}$  to list of old enable channel funding keys
51: add hostP to list of old hosts
52: assign received host to hostP
53:  $c_P \leftarrow c_P + c'_1$ ;  $c_{\bar{P}} \leftarrow c_{\bar{P}} + c'_2$ 
54: layer  $\leftarrow$  layer - 1
55:  $\text{locked}_P \leftarrow \text{locked}_P - c_{\text{virt}}$ 
56:  $State \leftarrow \text{OPEN}$ 
57: input (REVOCATION,  $\text{sig}_{P,R,i}$ ) to last old host
58: rename received signature to  $\text{sig}_{1,\text{right},R}$  // executed by hostP
59:  $R_{\text{rem},\text{virt}} \leftarrow \text{TX}$  {input: ( $c_{\text{virt}}, 4/\{pk_{1,\text{rev}}, pk_{1,\text{rev}}, pk_{2,\text{rev}}, pk_{n,\text{rev}}\}$ ), output:
    ( $c_{\text{virt}}, pk_{2,\text{out}}$ )}}
60:  $\text{sig}_{1,\text{right},\text{rev},\text{virt}} \leftarrow \text{SIGN}(R_{\text{rem},\text{virt}}, sk_{1,\text{rev}})$ 
61:  $R_{\text{rem},\text{fund}} \leftarrow \text{TX}$  {input: ( $c_P + c_{\bar{P}}, 2/\{pk_{1,\text{rev}}, pk_{2,\text{rev}}\}$ ), output:
    ( $c_P + c_{\bar{P}}, pk_{2,\text{out}}$ )}}
62:  $\text{sig}_{1,\text{right},\text{rev},\text{fund}} \leftarrow \text{SIGN}(R_{\text{rem},\text{fund}}, sk_{1,\text{rev}})$ 
63: for all  $j \in \{2, \dots, n\}$  do
64:    $R_{j,\text{left}} \leftarrow \text{TX}$  {input: ( $c_{\text{virt}}, 4/\{pk_{1,\text{rev}}, pk_{j-1,\text{rev}}, pk_{j,\text{rev}}, pk_{n,\text{rev}}\}$ ), output:
    ( $c_{\text{virt}}, pk_{j,\text{out}}$ )}}
65:    $\text{sig}_{1,j,\text{left},\text{rev}} \leftarrow \text{SIGN}(R_{j,\text{left}}, sk_{1,\text{rev}})$ 
66: end for
67:  $State \leftarrow \text{COOP CLOSED}$ 

```

```

68: send (COOP CLOSE REVOCATIONS, (sig1,right,R, sig1,right,rev,virt, sig1,right,rev,fund,
    (sig1,j,left,rev)j∈{2,...,n})) to  $\bar{P}$ 

```

Fig. 47.

Process LN – On (CORRUPT) by \mathcal{A} or kindred party R :

```

// This is executed by the shell – c.f. [13]
1: if State ≠ CORRUPTED then
2:   State ← CORRUPTED
3:   for  $S \in$  set of kindred parties do
4:     input (CORRUPT) to  $S$  and expect reply (OK)
5:   end for
6: end if
7: reply (OK)

```

Fig. 48.

Process VIRT

```

1: On every activation, before handling the message:
2:   if last_poll ≠ ⊥ then // virtual layer is ready
3:     input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
4:     if last_poll + p <  $|\Sigma|$  then
5:       for  $P \in \{\text{guest, funder, fundee}\}$  do // at most 1 of funder, fundee
        is defined
6:         ensure  $P.\text{NEGLIGENT}()$  returns (OK)
7:       end for
8:     end if
9:   end if

10: // guest is trusted to give sane inputs, therefore a state machine and input
    verification are redundant
11: On input (INIT, hostP,  $\bar{P}$ , sibling, fundee, (skloc,fund,new, pkloc,fund,new),
    pkrem,fund,new, pksib,rem,fund,new, (skloc,fund,old, pkloc,fund,old), pkrem,fund,old,
    pkloc,out, cP, c $\bar{P}$ , cvirt, tP, i, side, n) by guest:
12:   ensure  $1 < i \leq n$  // host_funder ( $i = 1$ ) is initialised with HOST ME
13:   ensure side ∈ {"left", "right"}
14:   store message contents and guest // sibling, pksib, $\bar{P}$ ,F are missing for
    endpoints, fundee is present only in last node
15:   (ski,fund,new, pki,fund,new) ← (skloc,fund,new, pkloc,fund,new)
16:   pkmyRem,fund,new ← pkrem,fund,new

```

```

17:   if  $i < n$  then // we are not last hop
18:        $pk_{\text{sibRem}, \text{fund}, \text{new}} \leftarrow pk_{\text{sib}, \text{rem}, \text{fund}, \text{new}}$ 
19:   end if
20:   if side = "left" then
21:        $\text{side}' \leftarrow \text{"right"}; \text{myRem} \leftarrow i - 1; \text{sibRem} \leftarrow i + 1$ 
22:        $pk_{i, \text{out}} \leftarrow pk_{\text{loc}, \text{out}}$ 
23:        $(sk_{i, j, k}, pk_{i, j, k})_{j \in \{2, \dots, n-1\}, k \in [n] \setminus \{j\}} \leftarrow \text{KEYGEN}^{(n-2)(n-1)}$ 
24:        $(sk_{i, \text{rev}}, pk_{i, \text{rev}}) \leftarrow \text{KEYGEN}()$ 
25:   else // side = "right"
26:        $\text{side}' \leftarrow \text{"left"}; \text{myRem} \leftarrow i + 1; \text{sibRem} \leftarrow i - 1$ 
27:       // sibling will send keys in KEYS AND COINS FORWARD
28:   end if
29:    $(sk_{i, \text{side}, \text{fund}, \text{old}}, pk_{i, \text{side}, \text{fund}, \text{old}}) \leftarrow (sk_{\text{loc}, \text{fund}, \text{old}}, pk_{\text{loc}, \text{fund}, \text{old}})$ 
30:    $pk_{\text{myRem}, \text{side}', \text{fund}, \text{old}} \leftarrow pk_{\text{rem}, \text{fund}, \text{old}}$ 
31:    $(c_{i, \text{side}}, c_{\text{myRem}, \text{side}', t_{i, \text{side}}}) \leftarrow (c_P, c_{\bar{P}}, t_P)$ 
32:   last_poll  $\leftarrow \perp$ 
33:   output (HOST INIT OK) to guest

34: On input (HOST ME, funder, fundee,  $\bar{P}$ ,  $\text{host}_P$ ,  $c_P$ ,  $c_{\bar{P}}$ ,  $c_{\text{virt}}$ ,  $pk_{\text{left}, \text{virt}}$ ,
 $pk_{\text{right}, \text{virt}}$ ,  $(sk_{1, \text{fund}, \text{new}}, pk_{1, \text{fund}, \text{new}})$ ,  $(sk_{1, \text{right}, \text{fund}, \text{old}}, pk_{1, \text{right}, \text{fund}, \text{old}})$ ,
 $pk_{2, \text{left}, \text{fund}, \text{old}}, pk_{2, \text{left}, \text{fund}, \text{new}}, pk_{1, \text{out}}, n$ ) by guest:
35:   last_poll  $\leftarrow \perp$ 
36:    $i \leftarrow 1$ 
37:    $c_{1, \text{right}} \leftarrow c_P; c_{2, \text{left}} \leftarrow c_{\bar{P}}$ 
38:    $(sk_{1, j, k}, pk_{1, j, k})_{j \in \{2, \dots, n-1\}, k \in [n] \setminus \{j\}} \leftarrow \text{KEYGEN}^{(n-2)(n-1)}$ 
39:    $(sk_{1, \text{rev}}, pk_{1, \text{loc}, \text{rev}}) \leftarrow \text{KEYGEN}()$ 
40:   ensure VIRT.CIRCULATEKEYSCoinsTimes() returns (OK)
41:   ensure VIRT.CIRCULATEVIRTUALSIGs() returns (OK)
42:   ensure VIRT.CIRCULATEFUNDINGSIGs() returns (OK)
43:   ensure VIRT.CIRCULATEREVOCATIONS() returns (OK)
44:   output (HOSTS READY,  $p + \sum_{j=2}^{n-1} (s - 1 + t_j)$ ) to guest //  $p$  is every how
many blocks we have to check the chain

```

Fig. 49.

Process VIRT.CIRCULATEKEYSCoinsTimes(left_data):

```

1: if left_data is given as argument then // we are not host_funder
2:   parse left_data as  $((pk_{j, \text{fund}, \text{new}})_{j \in [i-1]}, (pk_{j, \text{left}, \text{fund}, \text{old}})_{j \in \{2, \dots, i-1\}},$ 
 $(pk_{j, \text{right}, \text{fund}, \text{old}})_{j \in [i-1]}, (pk_{j, \text{out}})_{j \in [i-1]}, (c_{j, \text{left}})_{j \in \{2, \dots, i-1\}}, (c_{j, \text{right}})_{j \in [i-1]},$ 
 $(t_j)_{j \in [i-1]}, pk_{\text{left}, \text{virt}}, pk_{\text{right}, \text{virt}}, (pk_{h, j, k})_{h \in [i-1], j \in \{2, \dots, n-1\}, k \in [n] \setminus \{j\}},$ 
 $(pk_{h, \text{loc}, \text{rev}})_{h \in [i-1]}, (pk_{h, \text{rem}, \text{rev}})_{h \in [i-1]})$ 
3:   if we have a sibling then // we are not host_fundee

```

```

4:      input (KEYS AND COINS FORWARD, (left_data, (ski,left,fund,old,
pki,left,fund,old), pki,out, ci,left, ti,left, (ski,j,k, pki,j,k)j∈{2,...,n-1}, k∈[n] \ {j},
(ski,rev, pki,rev)) to sibling
5:      store input as left_data and parse it as ((pkj,fund,new)j∈[i-1],
(pkj,left,fund,old)j∈{2,...,i}, (pkj,right,fund,old)j∈[i-1], (pkj,out)j∈[i], (cj,left)j∈{2,...,i},
(cj,right)j∈[i-1], (tj)j∈[i-1], ski,left,fund,old, ti,left, pkleft,virt, pkright,virt,
(pkh,j,k)h∈[i], j∈{2,...,n-1}, k∈[n] \ {j}, (ski,j,k)j∈{2,...,n-1}, k∈[n] \ {j}, (pkh,rev)h∈[i],
ski,rev
6:      ti ← max(ti,left, ti,right)
7:      replace ti,left in left_data with ti
8:      remove ski,left,fund,old, (ski,j,k)j∈{2,...,n-1}, k∈[n] \ {j}, ski,loc,rev and
ski,rem,rev from left_data
9:      call VIRT.CIRCULATEKEYSCOINSTIMES(left_data) of  $\bar{P}$  and assign
returned value to right_data
10:     parse right_data as ((pkj,fund,new)j∈{i+1,...,n},
(pkj,left,fund,old)j∈{i+1,...,n}, (pkj,right,fund,old)j∈{i+1,...,n-1}, (pkj,out)j∈{i+1,...,n},
(cj,left)j∈{i+1,...,n}, (cj,right)j∈{i+1,...,n-1}, (tj)j∈{i+1,...,n},
(pkh,j,k)h∈{i+1,...,n}, j∈{2,...,n-1}, k∈[n] \ {j}, (pkh,rev)h∈{i+1,...,n})
11:     output (KEYS AND COINS BACK, right_data, (ski,right,fund,old,
pki,right,fund,old), ci,right, ti)
12:     store output as right_data and parse it as ((pkj,fund,new)j∈{i+1,...,n},
(pkj,left,fund,old)j∈{i+1,...,n}, (pkj,right,fund,old)j∈{i,...,n-1}, (pkj,out)j∈{i+1,...,n},
(cj,left)j∈{i+1,...,n}, (cj,right)j∈{i,...,n-1}, (tj)j∈{i,...,n},
(pkh,j,k)h∈{i+1,...,n}, j∈{2,...,n-1}, k∈[n] \ {j}, (pkh,loc,rev)h∈{i+1,...,n},
(pkh,rem,rev)h∈{i+1,...,n}, ski,right,fund,old)
13:     remove ski,right,fund,old from right_data
14:     return (right_data, pki,fund,new, pki,left,fund,old, pki,out, ci,left)
15:   else // we are host_fundee
16:     output (CHECK KEYS, (pkleft,virt, pkright,virt)) to fundee and expect
reply (KEYS OK)
17:     return (pkn,fund,new, pkn,left,fund,old, pkn,out, cn,left, tn,
(pkn,j,k)j∈{2,...,n-1}, k∈[n] \ {j}, pkn,loc,rev, pkn,rem,rev)
18:   end if
19: else // we are host_funder
20:   call VIRT.CIRCULATEKEYSCOINSTIMES(pk1,fund,new, pk1,right,fund,old, pk1,out,
c1,right, t1, pkleft,virt, pkright,virt, (pk1,j,k)j∈{2,...,n-1}, k∈[n] \ {j}, pk1,loc,rev,
pk1,rem,rev) of  $\bar{P}$  and assign returned value to right_data
21:   parse right_data as ((pkj,fund,new)j∈{2,...,n}, (pkj,left,fund,old)j∈{2,...,n},
(pkj,right,fund,old)j∈{2,...,n-1}, (pkj,out)j∈{2,...,n}, (cj,left)j∈{2,...,n},
(cj,right)j∈{2,...,n-1}, (tj)j∈{2,...,n}, (pkh,j,k)h∈{2,...,n}, j∈{2,...,n-1}, k∈[n] \ {j},
(pkh,loc,rev)h∈{2,...,n}, (pkh,rem,rev)h∈{2,...,n})
22:   return (OK)
23: end if

```

Fig. 50.

Process VIRT

```

1: GETMIDTXS( $i, n, c_{\text{virt}}, c_{\text{rem},\text{left}}, c_{\text{loc},\text{left}}, c_{\text{loc},\text{right}}, c_{\text{rem},\text{right}}, pk_{\text{rem},\text{left},\text{fund},\text{old}},$ 
 $pk_{\text{loc},\text{left},\text{fund},\text{old}}, pk_{\text{loc},\text{right},\text{fund},\text{old}}, pk_{\text{rem},\text{right},\text{fund},\text{old}}, pk_{\text{rem},\text{left},\text{fund},\text{new}},$ 
 $pk_{\text{loc},\text{left},\text{fund},\text{new}}, pk_{\text{loc},\text{right},\text{fund},\text{new}}, pk_{\text{rem},\text{right},\text{fund},\text{new}}, pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}},$ 
 $pk_{\text{loc},\text{out}}, pk_{\text{funder},\text{rev}}, pk_{\text{left},\text{rev}}, pk_{\text{loc},\text{rev}}, pk_{\text{right},\text{rev}}, pk_{\text{fundee},\text{rev}},$ 
 $(pk_{h,j,k})_{h \in [n], j \in [n-1] \setminus \{1\}, k \in [n-1] \setminus \{1,j\}}, (pk_{h,2,1})_{h \in [n]}, (pk_{h,n-1,n})_{h \in [n]},$ 
 $(t_j)_{j \in [n-1] \setminus \{1\}})$ :
2:   ensure  $1 < i < n$ 
3:   ensure  $c_{\text{rem},\text{left}} \geq c_{\text{virt}} \wedge c_{\text{loc},\text{left}} \geq c_{\text{virt}}$  // left parties fund virtual channel
4:   ensure  $c_{\text{rem},\text{left}} \geq c_{\text{loc},\text{right}} \wedge c_{\text{rem},\text{right}} \geq c_{\text{loc},\text{left}}$  // avoid griefing attack
5:    $c_{\text{left}} \leftarrow c_{\text{rem},\text{left}} + c_{\text{loc},\text{left}}; c_{\text{right}} \leftarrow c_{\text{loc},\text{right}} + c_{\text{rem},\text{right}}$ 
6:    $\text{left\_old\_fund} \leftarrow 2/\{pk_{\text{rem},\text{left},\text{fund},\text{old}}, pk_{\text{loc},\text{left},\text{fund},\text{old}}\}$ 
7:    $\text{right\_old\_fund} \leftarrow 2/\{pk_{\text{loc},\text{right},\text{fund},\text{old}}, pk_{\text{rem},\text{right},\text{fund},\text{old}}\}$ 
8:    $\text{left\_new\_fund} \leftarrow$ 
 $2/\{pk_{\text{rem},\text{left},\text{fund},\text{new}}, pk_{\text{loc},\text{left},\text{fund},\text{new}}\} \vee 2/\{pk_{\text{left},\text{rev}}, pk_{\text{loc},\text{rev}}\}$ 
9:    $\text{right\_new\_fund} \leftarrow$ 
 $2/\{pk_{\text{loc},\text{right},\text{fund},\text{new}}, pk_{\text{rem},\text{right},\text{fund},\text{new}}\} \vee 2/\{pk_{\text{loc},\text{rev}}, pk_{\text{right},\text{rev}}\}$ 
10:   $\text{virt\_fund} \leftarrow 2/\{pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}}\}$ 
11:   $\text{revocation} \leftarrow 4/\{pk_{\text{funder},\text{rev}}, pk_{\text{loc},\text{rev}}, pk_{\text{right},\text{rev}}, pk_{\text{fundee},\text{rev}}\}$ 
12:   $\text{refund} \leftarrow (pk_{\text{loc},\text{out}} + (p + s)) \vee 2/\{pk_{\text{left},\text{rev}}, pk_{\text{loc},\text{rev}}\}$ 
13:  for all  $j \in [n-1] \setminus \{1\}, k \in [n-1] \setminus \{1,j\}$  do
14:     $\text{all}_{j,k} \leftarrow n/\{pk_{1,j,k}, \dots, pk_{n,j,k}\} \wedge "k"$ 
15:  end for
16:  if  $i = 2$  then
17:     $\text{all}_{2,1} \leftarrow n/\{pk_{1,2,1}, \dots, pk_{n,2,1}\} \wedge "1"$ 
18:  end if
19:  if  $i = n-1$  then
20:     $\text{all}_{n-1,n} \leftarrow n/\{pk_{1,n-1,n}, \dots, pk_{n,n-1,n}\} \wedge "n"$ 
21:  end if
22:  if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
23:  if  $i = n-1$  then  $l \leftarrow n$  else  $l \leftarrow n-1$ 
24:   $\text{bridge}_1 \leftarrow 4/\{pk_{1,2,1}, pk_{i-1,2,1}, pk_{i+1,2,1}, pk_{n,2,1}\} \wedge "1"$  // We reuse the
 $pk_{j,2,1}$  keys for all bridges to avoid new keys
25:   $\text{revocation}_1 \leftarrow 4/\{pk_{\text{funder},\text{rev}}, pk_{\text{loc},\text{rev}}, pk_{\text{right},\text{rev}}, pk_{\text{fundee},\text{rev}}\} \wedge "1"$ 
26:  for all  $k \in \{m, \dots, l\} \setminus \{i\}$  do
27:     $\text{bridge}_{2,k} \leftarrow 4/\{pk_{1,2,1}, pk_{i-1,2,1}, pk_{i+1,2,1}, pk_{n,2,1}\} \wedge "2,k"$ 
28:     $\text{revocation}_{2,k} \leftarrow 4/\{pk_{\text{funder},\text{rev}}, pk_{\text{loc},\text{rev}}, pk_{\text{right},\text{rev}}, pk_{\text{fundee},\text{rev}}\} \wedge "2,k"$ 
29:  end for
30:  for all  $(k_1, k_2) \in \{m, \dots, i-1\} \times \{i+1, \dots, l\}$  do
31:     $\text{bridge}_{3,k_1,k_2} \leftarrow 4/\{pk_{1,2,1}, pk_{i-1,2,1}, pk_{i+1,2,1}, pk_{n,2,1}\} \wedge "3,k_1,k_2"$ 
32:   $\text{revocation}_{3,k_1,k_2} \leftarrow 4/\{pk_{\text{funder},\text{rev}}, pk_{\text{loc},\text{rev}}, pk_{\text{right},\text{rev}}, pk_{\text{fundee},\text{rev}}\} \wedge "3,k_1,k_2"$ 
33:  end for
34:  // After funding is complete,  $A_j$  has the signature of all other parties for
  all  $\text{all}_{j,k}$  and bridge inputs, but other parties do not have  $A_j$ 's signature for
  this input, therefore only  $A_j$  can publish it.
35:  //  $\text{TX}_{i,j,k} := i$ -th move,  $j, k$  input interval start and end.  $j, k$  unneeded for
 $i = 1, k$  unneeded for  $i = 2$ .

```

```

36: TX1 ← TX:
37:   inputs:
38:     (cleft, left_old_fund),
39:     (cright, right_old_fund)
40:   outputs:
41:     (cleft - cvirt, left_new_fund),
42:     (cright - cvirt, right_new_fund),
43:     (cvirt, refund),
44:     (cvirt,
45:       (if (i - 1 > 1) then alli-1,i else False)
46:       ∨ (if (i + 1 < n) then alli+1,i else False)
47:       ∨ revocation1
48:       ∨ (
49:         if (i - 1 = 1 ∧ i + 1 = n) then bridge1
50:         else if (i - 1 > 1 ∧ i + 1 = n) then bridge1 + ti-1
51:         else if (i - 1 = 1 ∧ i + 1 < n) then bridge1 + ti+1
52:         else /*i - 1 > 1 ∧ i + 1 < n*/ bridge1 + max(ti-1, ti+1)
53:       )
54:     )
55: B1 ← TX:
56:   input:
57:     (cvirt, bridge1)
58:   output:
59:     (cvirt, revocation ∨ virt_fund)
60: if i = 2 then
61:   TX2,1 ← TX:
62:     inputs:
63:       (cvirt, all2,1),
64:       (cright, right_old_fund)
65:     outputs:
66:       (cright - cvirt, right_new_fund),
67:       (cvirt, refund),
68:       (cvirt,
69:         (if (n > 3) then (all3,2 ∨ revocation2,1 ∨ (bridge2,1 + t3))
70:         else revocation2,1 ∨ bridge2,1)
71:       )
72:   B2,1 ← TX:
73:     input:
74:       (cvirt, bridge2,1)
75:     output:
76:       (cvirt, revocation ∨ virt_fund)
77: end if
78: if i = n - 1 then

```

```

79:   TX2,n ← TX:
80:     inputs:
81:       (cleft, left_old_fund),
82:       (cvirt, alln-1,n)
83:     outputs:
84:       (cleft - cvirt, left_new_fund),
85:       (cvirt, refund),
86:       (cvirt,
87:        (if (n - 2 > 1) then
25: (alln-2,n-1 ∨ revocation2,n ∨ (bridge2,n + tn-2))
88:        else revocation2,n ∨ bridge2,n)
89:        )
90:   B2,n ← TX:
91:     input:
92:       (cvirt, bridge2,n)
93:     output:
94:       (cvirt, revocation ∨ virt_fund)
95:   end if
96:   for all k ∈ {2, ..., i - 1} do // 2(i - 2) txs
97:     TX2,k ← TX:
98:       inputs:
99:         (cvirt, alli,k),
100:        (cright, right_old_fund)
101:       outputs:
102:         (cright - cvirt, right_new_fund),
103:         (cvirt, refund),
104:         (cvirt,
105:          (if (k - 1 > 1) then allk-1,i else False)
106:          ∨ (if (i + 1 < n) then alli+1,k else False)
107:          ∨ revocation2,k
108:          ∨ (
109:            if (k - 1 = 1 ∧ i + 1 = n) then bridge2,k
110:            else if (k - 1 > 1 ∧ i + 1 = n) then bridge2,k + tk-1
111:            else if (k - 1 = 1 ∧ i + 1 < n) then bridge2,k + ti+1
112:            else /*k - 1 > 1 ∧ i + 1 < n*/
113:              bridge2,k + max(tk-1, ti+1)
114:          )
115:        )
116:   B2,k ← TX:
117:     input:
118:       (cvirt, bridge2,k)
119:     output:

```

```

120:      ( $c_{\text{virt}}$ , revocation  $\vee$  virt_fund)
121: end for
122: for all  $k \in \{i+1, \dots, n-1\}$  do //  $2(n-i-1)$  txs
123:    $\text{TX}_{2,k} \leftarrow \text{TX}$ :
124:     inputs:
125:       ( $c_{\text{left}}$ , left_old_fund)
126:       ( $c_{\text{virt}}$ ,  $\text{all}_{i,k}$ ),
127:     outputs:
128:       ( $c_{\text{left}} - c_{\text{virt}}$ , left_new_fund),
129:       ( $c_{\text{virt}}$ , refund),
130:       ( $c_{\text{virt}}$ ,
131:        (if  $(i-1 > 1)$  then  $\text{all}_{i-1,k}$  else False)
132:         $\vee$  (if  $(k+1 < n)$  then  $\text{all}_{k+1,i}$  else False)
133:         $\vee$  revocation $_{2,k}$ 
134:         $\vee$  (
135:          if  $(i-1 = 1 \wedge k+1 = n)$  then bridge $_{2,k}$ 
136:          else if  $(i-1 > 1 \wedge k+1 = n)$  then bridge $_{2,k} + t_{i-1}$ 
137:          else if  $(i-1 = 1 \wedge k+1 < n)$  then bridge $_{2,k} + t_{k+1}$ 
138:          else  $\text{all}_{i-1 > 1 \wedge k+1 < n}$ 
139:          bridge $_{2,k} + \max(t_{i-1}, t_{k+1})$ 
140:        )
141:      )
142:    $B_{2,k} \leftarrow \text{TX}$ :
143:     input:
144:       ( $c_{\text{virt}}$ , bridge $_{2,k}$ )
145:     output:
146:       ( $c_{\text{virt}}$ ,  $\vee$  revocation  $\vee$  virt_fund)
147: end for
148: for all  $(k_1, k_2) \in \{m, \dots, i-1\} \times \{i+1, \dots, l\}$  do //  $(i-m) \cdot (l-i)$  txs
149:    $\text{TX}_{3,k_1,k_2} \leftarrow \text{TX}$ :
150:     inputs:
151:       ( $c_{\text{virt}}$ ,  $\text{all}_{i,k_1}$ ),
152:       ( $c_{\text{virt}}$ ,  $\text{all}_{i,k_2}$ )
153:     outputs:
154:       ( $c_{\text{virt}}$ , refund),
155:       ( $c_{\text{virt}}$ ,
156:        (if  $(k_1-1 > 1)$  then  $\text{all}_{k_1-1, \min(k_2, n-1)}$  else False)
157:         $\vee$  (if  $(k_2+1 < n)$  then  $\text{all}_{k_2+1, \max(k_1, 2)}$  else False)
158:         $\vee$  revocation $_{3,k_1,k_2}$ 
159:         $\vee$  (
160:          if  $(k_1-1 \leq 1 \wedge k_2+1 \geq n)$  then bridge $_{3,k_1,k_2}$ 
161:          else if  $(k_1-1 > 1 \wedge k_2+1 \geq n)$  then bridge $_{3,k_1,k_2} + t_{k_1-1}$ 
162:          else if  $(k_1-1 \leq 1 \wedge k_2+1 < n)$  then bridge $_{3,k_1,k_2} + t_{k_2+1}$ 

```

```

163:             else /* $k_1 - 1 > 1 \wedge k_2 + 1 < n^*$ */
164:                 bridge3, $k_1,k_2$  + max( $t_{k_1-1}, t_{k_2+1}$ )
165:             )
166:         )
167:      $B_{3,k_1,k_2} \leftarrow \text{TX}$ :
168:         input:
169:             ( $c_{\text{virt}}$ , bridge3, $k_1,k_2$ )
170:         output:
171:             ( $c_{\text{virt}}$ ,  $\vee$  revocation  $\vee$  virt_fund)
172:     end for
173:     return (
174:          $\text{TX}_1, B_1,$ 
175:         ( $\text{TX}_{2,k}, B_{2,k}$ ) $_{k \in \{m, \dots, l\} \setminus \{i\}},$ 
176:         ( $\text{TX}_{3,k_1,k_2}, B_{3,k_1,k_2}$ ) $_{(k_1,k_2) \in \{m, \dots, i-1\} \times \{i+1, \dots, l\}}$ 
177:     )

```

Fig. 51.

Process VIRT

```

1: // left and right refer to the two counterparties, with left being the one closer
   to the funder. Note difference with left/right meaning in VIRT.GETMIDTXs.
2: GETENDPOINTTX( $i, n, c_{\text{virt}}, c_{\text{left}}, c_{\text{right}}, pk_{\text{left,fund,old}}, pk_{\text{right,fund,old}},$ 
    $pk_{\text{left,fund,new}}, pk_{\text{right,fund,new}}, pk_{\text{left,virt}}, pk_{\text{right,virt}}, pk_{\text{interm,rev}}, pk_{\text{endpoint,rev}},$ 
   ( $pk_{\text{all},j}$ ) $_{j \in [n]}, t$ ):
3:   ensure  $i \in \{1, n\}$ 
4:   ensure  $c_{\text{left}} \geq c_{\text{virt}}$  // left party funds virtual channel
5:    $c_{\text{tot}} \leftarrow c_{\text{left}} + c_{\text{right}}$ 
6:   old_fund  $\leftarrow 2/\{pk_{\text{left,fund,old}}, pk_{\text{right,fund,old}}\}$ 
7:   new_fund  $\leftarrow 2/\{pk_{\text{left,fund,new}}, pk_{\text{right,fund,new}}\} \vee 2/\{pk_{\text{left,rev}}, pk_{\text{right,rev}}\}$ 
8:   virt_fund  $\leftarrow 2/\{pk_{\text{left,virt}}, pk_{\text{right,virt}}\}$ 
9:   revocation  $\leftarrow \text{revocation}_1 \leftarrow 2/\{pk_{\text{interm,rev}}, pk_{\text{endpoint,rev}}\}$ 
10:  if  $i = 1$  then // funder's tx
11:     $\text{all} \leftarrow n/\{pk_{\text{all},1}, \dots, pk_{\text{all},n}\} \wedge "1"$ 
12:    bridge  $\leftarrow 2/\{pk_{\text{all},2}, pk_{\text{all},n}\} \wedge "1"$  // We reuse the  $pk_{\text{all},j}$  keys to avoid
        new keys
13:  else //  $i = n$ , fundee's tx
14:     $\text{all} \leftarrow n/\{pk_{\text{all},1}, \dots, pk_{\text{all},n}\} \wedge "n"$ 
15:    bridge  $\leftarrow 2/\{pk_{\text{all},1}, pk_{\text{all},n-1}\} \wedge "1"$ 
16:  end if
17:   $\text{TX}_1 \leftarrow \text{TX}$ : // endpoints only have an "initiator" tx
18:    input:

```

```

19:      ( $c_{\text{tot}}$ ,  $\text{old\_fund}$ )
20:      outputs:
21:      ( $c_{\text{tot}} - c_{\text{virt}}$ ,  $\text{new\_fund}$ ),
22:      ( $c_{\text{virt}}$ ,  $\text{all} \vee \text{revocation}_1 \vee (\text{bridge} + t)$ )
23:   $B_1 \leftarrow \text{TX}$ :
24:      input:
25:      ( $c_{\text{virt}}$ ,  $\text{bridge}$ )
26:      output:
27:      ( $c_{\text{virt}}$ ,  $\text{revocation} \vee \text{virt\_fund}$ )
28:  return  $\text{TX}_1$ ,  $B_1$ 

```

Fig. 52.

Process VIRT.SIBLINGSIGS()

```

1: parse input as  $\text{sigs}_{\text{byLeft}}$ 
2: if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
3: if  $i = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 
4: ( $\text{TX}_{i,1}$ ,  $B_{i,1}$ ,  $(\text{TX}_{i,2,k}, B_{i,2,k})_{k \in \{m, \dots, l\} \setminus \{i\}}$ ,
   ( $\text{TX}_{i,3,k_1,k_2}, B_{i,3,k_1,k_2})_{(k_1,k_2) \in \{m, \dots, i-1\} \times \{i+1, \dots, l\}}$ )  $\leftarrow \text{VIRT.GETMIDTXS}(i, n,$ 
    $c_{\text{virt}}$ ,  $c_{i-1,\text{right}}$ ,  $c_{i,\text{left}}$ ,  $c_{i,\text{right}}$ ,  $c_{i+1,\text{left}}$ ,  $pk_{i-1,\text{right},\text{fund},\text{old}}$ ,  $pk_{i,\text{left},\text{fund},\text{old}}$ ,
    $pk_{i,\text{right},\text{fund},\text{old}}$ ,  $pk_{i+1,\text{left},\text{fund},\text{old}}$ ,  $pk_{i-1,\text{fund},\text{new}}$ ,  $pk_{i,\text{fund},\text{new}}$ ,  $pk_{i,\text{fund},\text{new}}$ ,
    $pk_{i+1,\text{fund},\text{new}}$ ,  $pk_{i,\text{left},\text{virt}}$ ,  $pk_{i,\text{right},\text{virt}}$ ,  $pk_{i,\text{out}}$ ,  $pk_{i,\text{rev}}$ ,  $pk_{i-1,\text{rev}}$ ,  $pk_{i,\text{rev}}$ ,  $pk_{i+1,\text{rev}}$ ,
    $pk_{n,\text{rev}}$ ,  $(pk_{h,j,k})_{h \in [n], j \in [n-1] \setminus \{1\}, k \in [n-1] \setminus \{1,j\}}$ ,  $(pk_{h,2,1})_{h \in [n]}$ ,  $(pk_{h,n-1,n})_{h \in [n]}$ ,
    $(t_h)_{h \in [n-1] \setminus \{1\}}$ )

5: // notation:  $\text{sig}(\text{TX}, pk) := \text{sig}$  with ANYPREVOUT flag such that
    $\text{VERIFY}(\text{TX}, \text{sig}, pk) = \text{True}$ 
6: ensure that the following signatures are present in  $\text{sigs}_{\text{byLeft}}$  and store them:
   - //  $(l - m) \cdot (i - 1)$  signatures
7:    $\forall k \in \{m, \dots, l\} \setminus \{i\}, \forall j \in [i - 1]$  :
8:      $\text{sig}(\text{TX}_{i,2,k}, pk_{j,i,k})$ 
   - //  $2 \cdot (i - m) \cdot (l - i) \cdot (i - 1)$  signatures
9:    $\forall k_1 \in \{m, \dots, i - 1\}, \forall k_2 \in \{i + 1, \dots, l\}, \forall j \in [i - 1]$  :
10:     $\text{sig}(\text{TX}_{i,3,k_1,k_2}, pk_{j,i,k_1}), \text{sig}(\text{TX}_{i,3,k_1,k_2}, pk_{j,i,k_2}),$ 
11:  $\text{sigs}_{\text{toRight}} \leftarrow \text{sigs}_{\text{byLeft}}$ 

12: if  $i + 1 = n$  then // next hop is host_fundee
13:    $\text{TX}_{n,1}, B_{n,1} \leftarrow \text{VIRT.GETENDPOINTTX}(n, n, c_{\text{virt}}$ ,  $c_{n-1,\text{right}}$ ,  $c_n,\text{left}$ ,
    $pk_{n-1,\text{right},\text{fund},\text{old}}$ ,  $pk_{n,\text{left},\text{fund},\text{old}}$ ,  $pk_{n-1,\text{fund},\text{new}}$ ,  $pk_{n,\text{fund},\text{new}}$ ,  $pk_{i,\text{left},\text{virt}}$ ,
    $pk_{i,\text{right},\text{virt}}$ ,  $pk_{n-1,\text{rev}}$ ,  $pk_{n,\text{rev}}$ ,  $(pk_{j,n-1,n})_{j \in [n]}$ ,  $t_{n-1}$ )
14:   add  $\text{SIGN}(B_{n,1}, sk_{i,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toRight}}$ 
15: end if

```

```

16: for all  $j \in \{2, \dots, n-1\} \setminus \{i\}$  do
17:   if  $j = 2$  then  $m' \leftarrow 1$  else  $m' \leftarrow 2$ 
18:   if  $j = n-1$  then  $l' \leftarrow n$  else  $l' \leftarrow n-1$ 
19:    $(TX_{j,1}, B_{j,1}, (TX_{j,2,k}, B_{j,2,k})_{k \in \{m', \dots, l'\} \setminus \{i\}},$ 
     $(TX_{j,3,k_1,k_2}, B_{j,3,k_1,k_2})_{(k_1,k_2) \in \{m', \dots, i-1\} \times \{i+1, \dots, l'\}}) \leftarrow \text{GETMIDTXS}(j, n, c_{\text{virt}},$ 
     $c_{j-1,\text{right}}, c_{j,\text{left}}, c_{j,\text{right}}, c_{j+1,\text{left}}, pk_{j-1,\text{right},\text{fund},\text{old}}, pk_{j,\text{left},\text{fund},\text{old}},$ 
     $pk_{j,\text{right},\text{fund},\text{old}}, pk_{j+1,\text{left},\text{fund},\text{old}}, pk_{j-1,\text{fund},\text{new}}, pk_{j,\text{fund},\text{new}}, pk_{j,\text{fund},\text{new}},$ 
     $pk_{j+1,\text{fund},\text{new}}, pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}}, pk_{j,\text{out}}, pk_{1,\text{rev}}, pk_{j-1,\text{rev}}, pk_{j,\text{rev}}, pk_{j+1,\text{rev}},$ 
     $pk_{n,\text{rev}}, (pk_{k,p,s})_{k \in [n], p \in [n-1] \setminus \{1\}, s \in [n-1] \setminus \{1,p\}}, (pk_{k,2,1})_{k \in [n]}, (pk_{k,n-1,n})_{k \in [n]},$ 
     $(t_k)_{k \in [n-1] \setminus \{1\}})$ 
20:   if  $j = i-1$  then
21:     ensure that the following signatures are present in  $\text{sigs}_{\text{byLeft}}$  and store
    them:
    - // 2 signatures
22:      $\text{sig}(B_{i-1,1}, pk_{1,2,1}), \text{sig}(B_{i-1,1}, pk_{i-1,2,1})$ 
    - //  $2(l-m)$  signatures
23:      $\forall k \in \{m, \dots, l\} \setminus \{i\} :$ 
24:      $\text{sig}(B_{i-1,2,k}, pk_{1,2,1}), \text{sig}(B_{i-1,2,k}, pk_{i-1,2,1})$ 
    - //  $2(i-m) \cdot (l-i)$  signatures
25:      $\forall k_1 \in \{m, \dots, i-1\}, \forall k_2 \in \{i+1, \dots, l\} :$ 
26:      $\text{sig}(B_{i-1,3,k_1,k_2}, pk_{1,2,1}), \text{sig}(B_{i-1,3,k_1,k_2}, pk_{i-1,2,1})$ 
27:   end if
28:   if  $j < i$  then  $\text{sigs} \leftarrow \text{sigs}_{\text{toLeft}}$  else  $\text{sigs} \leftarrow \text{sigs}_{\text{toRight}}$ 
29:   if  $i \in \{1, n\} \vee j \in \{i-1, i+1\}$  then
30:     add  $\text{SIGN}(B_{j,1}, sk_{i,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}$ 
31:   end if
32:   for all  $k \in \{m', \dots, l'\} \setminus \{j\}$  do
33:     add  $\text{SIGN}(TX_{j,2,k}, sk_{i,j,k}, \text{ANYPREVOUT})$  to  $\text{sigs}$ 
34:     if  $i \in \{1, n\} \vee j \in \{i-1, i+1\}$  then
35:       add  $\text{SIGN}(B_{j,2,k}, sk_{i,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}$ 
36:     end if
37:   end for
38:   for all  $k_1 \in \{m', \dots, j-1\}, k_2 \in \{j+1, \dots, l'\}$  do
39:     add  $\text{SIGN}(TX_{j,3,k_1,k_2}, sk_{i,j,k_1}, \text{ANYPREVOUT})$  to  $\text{sigs}$ 
40:     add  $\text{SIGN}(TX_{j,3,k_1,k_2}, sk_{i,j,k_2}, \text{ANYPREVOUT})$  to  $\text{sigs}$ 
41:     if  $i \in \{1, n\} \vee j \in \{i-1, i+1\}$  then
42:       add  $\text{SIGN}(B_{j,3,k_1,k_2}, sk_{i,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}$ 
43:     end if
44:   end for
45: end for

46: call  $\bar{P}.\text{CIRCULATEVIRTUALSIGS}(\text{sigs}_{\text{toRight}})$  and assign returned value to
 $\text{sigs}_{\text{byRight}}$ 
47: output  $(\text{VIRTUALSIGSBACK}, \text{sigs}_{\text{toLeft}}, \text{sigs}_{\text{byRight}})$ 

```

Fig. 53.

Process VIRT.INTERMEDIARYSIGS()

```

1: if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
2: if  $i = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 
3:  $(TX_{i,1}, B_{i,1}, (TX_{i,2,k}, B_{i,2,k})_{k \in \{m, \dots, l\} \setminus \{i\}},$ 
    $(TX_{i,3,k_1,k_2}, B_{i,3,k_1,k_2})_{(k_1,k_2) \in \{m, \dots, i-1\} \times \{i+1, \dots, l\}}) \leftarrow \text{VIRT.GETMIDTXS}(i, n,$ 
    $c_{\text{virt}}, c_{i-1, \text{right}}, c_{i, \text{left}}, c_{i, \text{right}}, c_{i+1, \text{left}}, pk_{i-1, \text{right}, \text{fund}, \text{old}}, pk_{i, \text{left}, \text{fund}, \text{old}},$ 
    $pk_{i, \text{right}, \text{fund}, \text{old}}, pk_{i+1, \text{left}, \text{fund}, \text{old}}, pk_{i-1, \text{fund}, \text{new}}, pk_{i, \text{fund}, \text{new}}, pk_{i, \text{fund}, \text{new}},$ 
    $pk_{i+1, \text{fund}, \text{new}}, pk_{\text{left}, \text{virt}}, pk_{\text{right}, \text{virt}}, pk_{i, \text{out}}, pk_{1, \text{rev}}, pk_{j-1, \text{rev}}, pk_{j, \text{rev}}, pk_{j+1, \text{rev}},$ 
    $pk_{n, \text{rev}}, (pk_{h,j,k})_{h \in [n], j \in [n-1] \setminus \{1\}, k \in [n-1] \setminus \{1, j\}}, (pk_{h,2,1})_{h \in [n]}, (pk_{h,n-1,n})_{h \in [n]},$ 
    $(t_h)_{h \in [n-1] \setminus \{1\}})$ 
4: // not verifying our signatures in  $\text{sig}_{\text{byLeft}}$ , our (trusted) sibling will do that
5: input (VIRTUAL SIGS FORWARD,  $\text{sig}_{\text{byLeft}}$ ) to sibling
6: VIRT.SIBLINGSIGS()
7:  $\text{sig}_{\text{toLeft}} \leftarrow \text{sig}_{\text{byRight}} + \text{sig}_{\text{toLeft}}$ 
8: if  $i = 2$  then // previous hop is host_funder
9:    $TX_{1,1}, B_{1,1} \leftarrow \text{VIRT.GETENDPOINTTX}(1, n, c_{\text{virt}}, c_{1, \text{right}}, c_{2, \text{left}},$ 
      $pk_{1, \text{right}, \text{fund}, \text{old}}, pk_{2, \text{left}, \text{fund}, \text{old}}, pk_{1, \text{fund}, \text{new}}, pk_{2, \text{fund}, \text{new}}, pk_{\text{left}, \text{virt}}, pk_{\text{right}, \text{virt}},$ 
      $pk_{2, \text{rev}}, pk_{1, \text{rev}}, (pk_{j,2,1})_{j \in [n]}, t_2)$ 
10:   add  $\text{SIGN}(B_{1,1}, sk_{i,2,1}, \text{ANYPREVOUT})$  to  $\text{sig}_{\text{toLeft}}$ 
11: end if
12: return  $\text{sig}_{\text{toLeft}}$ 

```

Fig. 54.

Process VIRT.HOSTFUNDEESIGS()

```

1:  $TX_{n,1}, B_{n,1} \leftarrow \text{VIRT.GETENDPOINTTX}(n, n, c_{\text{virt}}, c_{n-1, \text{right}}, c_{n, \text{left}},$ 
    $pk_{n-1, \text{right}, \text{fund}, \text{old}}, pk_{n, \text{right}, \text{fund}, \text{old}}, pk_{n-1, \text{fund}, \text{new}}, pk_{n, \text{fund}, \text{new}}, pk_{\text{left}, \text{virt}},$ 
    $pk_{\text{right}, \text{virt}}, pk_{n-1, \text{rev}}, pk_{n, \text{rev}}, (pk_{j,n-1,n})_{j \in [n]}, t_{n-1})$ 
2: ensure that  $\text{sig}(B_{n,1}, pk_{1,2,1}), \text{sig}(B_{n,1}, pk_{n-1,2,1})$  are present in  $\text{sig}_{\text{byLeft}}$  and
   store them
3:  $\text{sig}_{\text{toLeft}} \leftarrow \emptyset$ 
4: for all  $j \in [n-1] \setminus \{1\}$  do
5:   if  $j = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
6:   if  $j = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 
7:    $(TX_{j,1}, B_{j,1}, (TX_{j,2,k}, B_{j,2,k})_{k \in \{m, \dots, l\} \setminus \{j\}},$ 
      $(TX_{j,3,k_1,k_2}, B_{j,3,k_1,k_2})_{(k_1,k_2) \in \{m, \dots, j-1\} \times \{j+1, \dots, l\}}) \leftarrow \text{VIRT.GETMIDTXS}(j, n,$ 
      $c_{\text{virt}}, c_{j-1, \text{right}}, c_{j, \text{left}}, c_{j, \text{right}}, c_{j+1, \text{left}}, pk_{j-1, \text{right}, \text{fund}, \text{old}}, pk_{j, \text{left}, \text{fund}, \text{old}},$ 
      $pk_{j, \text{right}, \text{fund}, \text{old}}, pk_{j+1, \text{left}, \text{fund}, \text{old}}, pk_{j-1, \text{fund}, \text{new}}, pk_{j, \text{fund}, \text{new}}, pk_{j, \text{fund}, \text{new}},$ 
      $pk_{j+1, \text{fund}, \text{new}}, pk_{\text{left}, \text{virt}}, pk_{\text{right}, \text{virt}}, pk_{j, \text{out}}, pk_{1, \text{rev}}, pk_{j-1, \text{rev}}, pk_{j, \text{rev}}, pk_{j+1, \text{rev}},$ 
      $pk_{n, \text{rev}}, (pk_{h,s,k})_{h \in [n], s \in [n-1] \setminus \{1\}, k \in [n-1] \setminus \{1, s\}}, (pk_{h,2,1})_{h \in [n]}, (pk_{h,n-1,n})_{h \in [n]},$ 
      $(t_h)_{h \in [n-1] \setminus \{1\}})$ 
8:   for all  $k \in \{m, \dots, l\} \setminus \{j\}$  do

```



```

9:      ensure that  $\text{sig}(B_{j,2,k}, pk_{1,2,1}), \text{sig}(B_{j,2,k}, pk_{n-1,2,1})$  are present in
       $\text{sigs}_{\text{byLeft}}$  and store them
10:      add  $\text{SIGN}(\text{TX}_{j,2,k}, sk_{n,j,k}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toLeft}}$ 
11:      add  $\text{SIGN}(B_{j,2,k}, sk_{n,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toLeft}}$ 
12:    end for
13:    for all  $k_1 \in \{m, \dots, j-1\}, k_2 \in \{j+1, \dots, l\}$  do
14:      ensure that  $\text{sig}(B_{j,3,k_1,k_2}, pk_{1,2,1}), \text{sig}(B_{j,3,k_1,k_2}, pk_{n-1,2,1})$  are present in
       $\text{sigs}_{\text{byLeft}}$  and store them
15:      add  $\text{SIGN}(\text{TX}_{j,3,k_1,k_2}, sk_{n,j,k_1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toLeft}}$ 
16:      add  $\text{SIGN}(\text{TX}_{j,3,k_1,k_2}, sk_{n,j,k_2}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toLeft}}$ 
17:      add  $\text{SIGN}(B_{j,3,k_1,k_2}, sk_{n,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toLeft}}$ 
18:    end for
19:  end for
20:  return  $\text{sigs}_{\text{toLeft}}$ 

```

Fig. 55.

Process VIRT.HOSTFUNDERSIGS()

```

1:  $\text{sigs}_{\text{toRight}} \leftarrow \emptyset$ 
2: for all  $j \in [n-1] \setminus \{1\}$  do
3:   if  $j = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
4:   if  $j = n-1$  then  $l \leftarrow n$  else  $l \leftarrow n-1$ 
5:    $(\text{TX}_{j,1}, B_{j,1}, (\text{TX}_{j,2,k}, B_{j,2,k})_{k \in \{m, \dots, l\} \setminus \{j\}},$ 
    $(\text{TX}_{j,3,k_1,k_2}, B_{j,3,k_1,k_2})_{(k_1,k_2) \in \{m, \dots, j-1\} \times \{j+1, \dots, l\}}) \leftarrow \text{VIRT.GETMIDTXS}(j, n,$ 
    $c_{\text{virt}}, c_{j-1,\text{right}}, c_{j,\text{left}}, c_{j,\text{right}}, c_{j+1,\text{left}}, pk_{j-1,\text{right},\text{fund},\text{old}}, pk_{j,\text{left},\text{fund},\text{old}},$ 
    $pk_{j,\text{right},\text{fund},\text{old}}, pk_{j+1,\text{left},\text{fund},\text{old}}, pk_{j-1,\text{fund},\text{new}}, pk_{j,\text{fund},\text{new}}, pk_{j,\text{fund},\text{new}},$ 
    $pk_{j+1,\text{fund},\text{new}}, pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}}, pk_{j,\text{out}}, pk_{1,\text{rev}}, pk_{j-1,\text{rev}}, pk_{j,\text{rev}}, pk_{j+1,\text{rev}},$ 
    $pk_{n,\text{rev}}, (pk_{h,s,k})_{h \in [n], s \in [n-1] \setminus \{1\}, k \in [n-1] \setminus \{1,s\}}, (pk_{h,2,1})_{h \in [n]}, (pk_{h,n-1,n})_{h \in [n]},$ 
    $(t_h)_{h \in [n-1] \setminus \{1\}})$ 
6:   for all  $k \in \{m, \dots, l\} \setminus \{j\}$  do
7:     add  $\text{SIGN}(\text{TX}_{j,2,k}, sk_{1,j,k}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toRight}}$ 
8:     add  $\text{SIGN}(B_{j,2,k}, sk_{1,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toRight}}$ 
9:   end for
10:  for all  $k_1 \in \{m, \dots, j-1\}, k_2 \in \{j+1, \dots, l\}$  do
11:    add  $\text{SIGN}(\text{TX}_{j,3,k_1,k_2}, sk_{1,j,k_1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toRight}}$ 
12:    add  $\text{SIGN}(\text{TX}_{j,3,k_1,k_2}, sk_{1,j,k_2}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toRight}}$ 
13:    add  $\text{SIGN}(B_{j,3,k_1,k_2}, sk_{1,2,1}, \text{ANYPREVOUT})$  to  $\text{sigs}_{\text{toRight}}$ 
14:  end for
15: end for
16: call  $\text{VIRT.CIRCULATEVIRTUALSIGS}(\text{sigs}_{\text{toRight}})$  of  $\bar{P}$  and assign output to
    $\text{sigs}_{\text{byRight}}$ 
17:  $\text{TX}_{1,1}, B_{1,1} \leftarrow \text{VIRT.GETENDPOINTTX}(1, n, c_{\text{virt}}, c_{1,\text{right}}, c_{2,\text{left}},$ 
    $pk_{1,\text{right},\text{fund},\text{old}}, pk_{2,\text{left},\text{fund},\text{old}}, pk_{1,\text{fund},\text{new}}, pk_{2,\text{fund},\text{new}}, pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}},$ 
    $pk_{2,\text{rev}}, pk_{1,\text{rev}}, (pk_{j,2,1})_{j \in [n]}, t_2)$ 

```

```

18: ensure that  $\text{sig}(B_{1,1}, pk_{2,2,1})$ ,  $\text{sig}(B_{1,1}, pk_{n,2,1})$  are present in  $\text{sigs}_{\text{byRight}}$  and
    store them
19: for all  $j \in [n-1] \setminus \{1\}$  do
20:   if  $j = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
21:   if  $j = n-1$  then  $l \leftarrow n$  else  $l \leftarrow n-1$ 
22:   for all  $k \in \{m, \dots, l\} \setminus \{j\}$  do
23:     ensure that  $\text{sig}(B_{j,2,k}, pk_{2,2,1})$ ,  $\text{sig}(B_{j,2,k}, pk_{n,2,1})$  are present in
     $\text{sigs}_{\text{byRight}}$  and store them
24:   end for
25:   for all  $k_1 \in \{m, \dots, j-1\}, k_2 \in \{j+1, \dots, l\}$  do
26:     ensure that  $\text{sig}(B_{j,3,k_1,k_2}, pk_{2,2,1})$ ,  $\text{sig}(B_{j,3,k_1,k_2}, pk_{n,2,1})$  are present in
     $\text{sigs}_{\text{byRight}}$  and store them
27:   end for
28: end for
29: return (OK)

```

Fig. 56.

Process VIRT.CIRCULATEVIRTUALSIGS($\text{sigs}_{\text{byLeft}}$)

```

1: if  $1 < i < n$  then // we are not host_funder nor host_fundee
2:   return VIRT.INTERMEDIARYSIGS()
3: else if  $i = 1$  then // we are host_funder
4:   return VIRT.HOSTFUNDERSIGS()
5: else if  $i = n$  then // we are host_fundee
6:   return VIRT.HOSTFUNDEESIGS()
7: end if // it is always  $1 \leq i \leq n$  - c.f. Fig. 49, l. 12 and l. 37

```

Fig. 57.

Process VIRT.CIRCULATEFUNDINGSIGS($\text{sigs}_{\text{byLeft}}$)

```

1: if  $1 < i < n$  then // we are not endpoint
2:   if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
3:   if  $i = n-1$  then  $l \leftarrow n$  else  $l \leftarrow n-1$ 
4:   ensure that the following signatures are present in  $\text{sigs}_{\text{byLeft}}$  and store them:
    - // 1 signature
5:      $\text{sig}(\text{TX}_{i,1}, pk_{i-1,\text{right},\text{fund},\text{old}})$ 
    - //  $n-3 + \chi_{i=2} + \chi_{i=n-1}$  signatures
6:      $\forall k \in \{m, \dots, l\} \setminus \{i\}$ 
7:      $\text{sig}(\text{TX}_{i,2,k}, pk_{i-1,\text{right},\text{fund},\text{old}})$ 

```

```

8:   input (VIRTUAL BASE SIG FORWARD, sigsbyLeft) to sibling
9:   extract and store sig(TXi,1, pki-1,right,fund,old) and  $\forall k \in \{m, \dots, l\} \setminus \{i\}$ 
   sig(TXi,2,k, pki-1,right,fund,old) from sigsbyLeft // same signatures as sibling
10:  sigstoRight  $\leftarrow$  {SIGN(TXi+1,1, ski,right,fund,old, ANYPREVOUT)}
11:  if  $i + 1 < n$  then
12:    if  $i + 1 = n - 1$  then  $l' \leftarrow n$  else  $l' \leftarrow n - 1$ 
13:    for all  $k \in \{2, \dots, l'\}$  do
14:      add SIGN(TXi+1,2,k, ski,right,fund,old, ANYPREVOUT) to sigstoRight
15:    end for
16:  else //  $i + 1 = n$ 
17:    add SIGN(TXn,1, ski,right,fund,old, ANYPREVOUT) to sigstoRight
18:  end if
19:  call VIRT.CIRCULATEFUNDINGSIGS(sigstoRight) of  $\bar{P}$  and assign returned
   values to sigsbyRight
20:  ensure that the following signatures are present in sigsbyRight and store
   them:
   - // 1 signature
21:   sig(TXi,1, pki+1,left,fund,old)
   - //  $n - 3 + \chi_{i=2} + \chi_{i=n-1}$  signatures
22:    $\forall k \in \{m, \dots, l\} \setminus \{i\}$ 
23:   sig(TXi,2,k, pki+1,right,fund,old)
24:  output (VIRTUAL BASE SIG BACK, sigsbyRight)
25:  extract and store sig(TXi,1, pki+1,right,fund,old) and  $\forall k \in \{m, \dots, l\} \setminus \{i\}$ 
   sig(TXi,2,k, pki+1,right,fund,old) from sigsbyRight // same signatures as sibling
26:  sigstoLeft  $\leftarrow$  {SIGN(TXi-1,1, ski,left,fund,old, ANYPREVOUT)}
27:  if  $i - 1 > 1$  then
28:    if  $i - 1 = 2$  then  $m' \leftarrow 1$  else  $m' \leftarrow 2$ 
29:    for all  $k \in \{m', \dots, n - 1\}$  do
30:      add SIGN(TXi-1,2,k, ski,left,fund,old, ANYPREVOUT) to sigstoLeft
31:    end for
32:  else //  $i - 1 = 1$ 
33:    add SIGN(TX1,1, ski,left,fund,old, ANYPREVOUT) to sigstoLeft
34:  end if
35:  return sigstoLeft
36: else if  $i = 1$  then // we are host_funder
37:  sigstoRight  $\leftarrow$  {SIGN(TX2,1, sk1,right,fund,old, ANYPREVOUT)}
38:  if  $2 = n - 1$  then  $l' \leftarrow n$  else  $l' \leftarrow n - 1$ 
39:  for all  $k \in \{3, \dots, l'\}$  do
40:    add SIGN(TX2,2,k, sk1,right,fund,old, ANYPREVOUT) to sigstoRight
41:  end for
42:  call VIRT.CIRCULATEFUNDINGSIGS(sigstoRight) of  $\bar{P}$  and assign returned
   value to sigsbyRight
43:  ensure that sig(TX1,1, pk2,left,fund,old) is present in sigsbyRight and store it
44:  return (OK)
45: else if  $i = n$  then // we are host_fundee
46:  ensure sig(TXn,1, pkn-1,right,fund,old) is present in sigsbyLeft and store it

```

```

47:   sigstoLeft  $\leftarrow$  {SIGN(TXn-1,1, skn,left,fund,old, ANYPREVOUT)}
48:   if  $n - 1 = 2$  then  $m' \leftarrow 1$  else  $m' \leftarrow 2$ 
49:   for all  $k \in \{m', \dots, n - 2\}$  do
50:     add SIGN(TXn-1,2,k, skn,left,fund,old, ANYPREVOUT) to sigstoLeft
51:   end for
52:   return sigstoLeft
53: end if // it is always  $1 \leq i \leq n$  - c.f. Fig. 49, l. 12 and l. 37

```

Fig. 58.

```

Process VIRT.CIRCULATEREVOCATIONS(revoc_by_prev)
1: if revoc_by_prev is given as argument then // we are not host_funder
2:   ensure guest.PROCESSREMOTEREVOCATION(revoc_by_prev) returns (OK)
3: else // we are host_funder
4:   revoc_for_next  $\leftarrow$  guest.REVOKEPREVIOUS()
5:   input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
6:   last_poll  $\leftarrow |\Sigma|$ 
7:   call VIRT.CIRCULATEREVOCATIONS(revoc_for_next) of  $\bar{P}$  and assign
   returned value to revoc_by_next
8:   ensure guest.PROCESSREMOTEREVOCATION(revoc_by_next) returns (OK)
   // If the "ensure" fails, the opening process freezes, this is intentional. The
   channel can still close via (FORCECLOSE)
9:   return (OK)
10: end if
11: if we have a sibling then // we are not host_fundee nor host_funder
12:   input (VIRTUAL REVOCATION FORWARD) to sibling
13:   revoc_for_next  $\leftarrow$  guest.REVOKEPREVIOUS()
14:   input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
15:   last_poll  $\leftarrow |\Sigma|$ 
16:   call VIRT.CIRCULATEREVOCATIONS(revoc_for_next) of  $\bar{P}$  and assign
   output to revoc_by_next
17:   ensure guest.PROCESSREMOTEREVOCATION(revoc_by_next) returns (OK)
18:   output (HOSTS READY,  $t_i$ ) to guest and expect reply (HOST ACK)
19:   output (VIRTUAL REVOCATION BACK)
20: end if
21: revoc_for_prev  $\leftarrow$  guest.REVOKEPREVIOUS()
22: if  $1 < i < n$  then // we are intermediary
23:   output (HOSTS READY,  $t_i$ ) to guest and expect reply (HOST ACK) //  $p$  is
   every how many blocks we have to check the chain
24: else // we are host_fundee, case of host_funder covered earlier
25:   output (HOSTS READY,  $p + \sum_{j=2}^{n-1} (s - 1 + t_j)$ ) to guest and expect reply
   (HOST ACK)
26: end if

```

```
27: return revoc_for_prev
```

Fig. 59.

Process VIRT – poll

```

1: On input (CHECK FOR LATERAL CLOSE) by  $R \in \{\text{guest, funder, fundee}\}$ :
2:   input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
3:    $k_1 \leftarrow 0$ 
4:   if  $\text{TX}_{i-1,1}$  is defined and  $\text{TX}_{i-1,1} \in \Sigma$  then
5:      $k_1 \leftarrow i - 1$ 
6:   end if
7:   for all  $k \in [i - 2]$  do
8:     if  $\text{TX}_{i-1,2,k}$  is defined and  $\text{TX}_{i-1,2,k} \in \Sigma$  then
9:        $k_1 \leftarrow k$ 
10:    end if
11:  end for
12:   $k_2 \leftarrow 0$ 
13:  if  $\text{TX}_{i+1,1}$  is defined and  $\text{TX}_{i+1,1} \in \Sigma$  then
14:     $k_2 \leftarrow i + 1$ 
15:  end if
16:  for all  $k \in \{i + 2, \dots, n\}$  do
17:    if  $\text{TX}_{i+1,2,k}$  is defined and  $\text{TX}_{i+1,2,k} \in \Sigma$  then
18:       $k_2 \leftarrow k$ 
19:    end if
20:  end for
21:   $\text{last\_poll} \leftarrow |\Sigma|$ 
22:  if  $k_1 > 0 \vee k_2 > 0$  then // at least one neighbour has published its TX
23:    ignore all messages except for (CHECK IF CLOSING) by  $R$ 
24:     $\text{State} \leftarrow \text{CLOSING}$ 
25:     $\text{sigs} \leftarrow \emptyset$ 
26:  end if
27:  if  $k_1 > 0 \wedge k_2 > 0$  then // both neighbours have published their TXs
28:    add  $(\text{sig}(\text{TX}_{i,3,k_1,k_2}, pk_{p,i,k_1}))_{p \in [n] \setminus \{i\}}$  to sigs
29:    add  $(\text{sig}(\text{TX}_{i,3,k_1,k_2}, pk_{p,i,k_2}))_{p \in [n] \setminus \{i\}}$  to sigs
30:    add  $\text{SIGN}(\text{TX}_{i,3,k_1,k_2}, sk_{i,i,k_1}, \text{ANYPREVOUT})$  to sigs
31:    add  $\text{SIGN}(\text{TX}_{i,3,k_1,k_2}, sk_{i,i,k_2}, \text{ANYPREVOUT})$  to sigs
32:    input (SUBMIT,  $\text{TX}_{i,3,k_1,k_2}$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$ 
33:  else if  $k_1 > 0$  then // only left neighbour has published its TX
34:    add  $(\text{sig}(\text{TX}_{i,2,k_1}, pk_{p,i,k_1}))_{p \in [n] \setminus \{i\}}$  to sigs
35:    add  $\text{SIGN}(\text{TX}_{i,2,k_1}, sk_{i,i,k_1}, \text{ANYPREVOUT})$  to sigs
36:    add  $\text{SIGN}(\text{TX}_{i,2,k_1}, sk_{i,\text{left},\text{fund},\text{old}}, \text{ANYPREVOUT})$  to sigs
37:    input (SUBMIT,  $\text{TX}_{i,2,k_1}$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$ 
38:  else if  $k_2 > 0$  then // only right neighbour has published its TX
39:    add  $(\text{sig}(\text{TX}_{i,2,k_2}, pk_{p,i,k_2}))_{p \in [n] \setminus \{i\}}$  to sigs

```

```

40:      add SIGN( $\text{TX}_{i,2,k_2}$ ,  $sk_{i,i,k_2}$ , ANYPREVOUT) to sigs
41:      add SIGN( $\text{TX}_{i,2,k_2}$ ,  $sk_{i,\text{right},\text{fund},\text{old}}$ , ANYPREVOUT) to sigs
42:      input (SUBMIT,  $\text{TX}_{i,2,k_2}$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$ 
43:  end if

44: On input (CHECK FOR REVOKED) by  $R \in \{\text{guest}, \text{funder}, \text{funde}\}$ :
45:   input (READ) to  $\mathcal{G}_{\text{Ledger}}$  and assign output to  $\Sigma$ 
46:   if  $\text{TX}_{i-1,1} \in \Sigma \vee \exists k \in \mathbb{N} : \text{TX}_{i-1,2,k} \in \Sigma$  then // left counterparty
maliciously published old virtual tx
47:     if  $\exists k \in \mathbb{N} : \text{TX}_{i-1,2,k} \in \Sigma$  then // exactly one of the two pairs is valid.
That is OK
48:        $(R_a, sk_a, R_b, sk_b) \leftarrow (R_{i-1,2,k}, sk_{i,2,1}, R_{\text{loc},\text{left},\text{virt}}, sk_{i,\text{rev}})$ 
49:     else
50:        $(R_a, sk_a, R_b, sk_b) \leftarrow (R_{i-1,1}, sk_{i,2,1}, R_{\text{loc},\text{left},\text{virt}}, sk_{i,\text{rev}})$ 
51:     end if
52:     input (SUBMIT,  $(R_a, R_b, R_{\text{loc},\text{left},\text{virt}}, R_{\text{loc},\text{left},\text{fund}})$ ,  $(\text{SIGN}(R_a, sk_a)$ ,
 $(\text{SIGN}(R_b, sk_b)$ ,  $\text{SIGN}(R_{\text{loc},\text{left},\text{virt}}, sk_{i,\text{rev}})$ ,  $\text{SIGN}(R_{\text{loc},\text{left},\text{fund}}, sk_{i,\text{rev}})))$  to  $\mathcal{G}_{\text{Ledger}}$ 
53:   end if
54:   if  $\text{TX}_{i+1,1} \in \Sigma \vee \exists k \in \mathbb{N} : \text{TX}_{i+1,2,k} \in \Sigma$  then // right counterparty
maliciously published old virtual tx
55:     input (SUBMIT,  $(R_{\text{loc},\text{right},\text{virt}}, R_{\text{loc},\text{right},\text{fund}})$ ,  $(\text{SIGN}(R_{\text{loc},\text{right},\text{virt}}, sk_{i,\text{rev}})$ ,
 $\text{SIGN}(R_{\text{loc},\text{right},\text{fund}}, sk_{i,\text{rev}})))$  to  $\mathcal{G}_{\text{Ledger}}$ 
56:   end if
57:   output (NOTHING REVOKED) to  $R$ 

```

Fig. 60.

Process VIRT – On input (FORCECLOSE) by R :

```

1: // At most one of funder, fundee is defined
2: ensure  $R \in \{\text{guest}, \text{funder}, \text{funde}\}$ 
3: if  $\text{State} = \text{CLOSED}$  then output (CLOSED) to  $R$ 
4: if  $\text{State} = \text{GUEST PUNISHED}$  then output (GUEST PUNISHED) to  $R$ 
5: ensure  $\text{State} \in \{\text{OPEN}, \text{CLOSING}\}$ 
6: if  $\text{host}_P \neq \mathcal{G}_{\text{Ledger}}$  then //  $\text{host}_P$  is a VIRT
7:   ignore all messages except for output (CLOSED) by  $\text{host}_P$ . Also relay to
 $\text{host}_P$  any (CHECK IF CLOSING) or (FORCECLOSE) input received
8:   input (FORCECLOSE) to  $\text{host}_P$ 
9: end if
10: // if we have a  $\text{host}_P$ , continue from here on output (CLOSED) by it
11: send (READ) to  $\mathcal{G}_{\text{Ledger}}$  as  $R$  and assign reply to  $\Sigma$ 
12: if  $i \in \{1, n\} \wedge (\text{TX}_{(i-1)+\frac{2}{n-1}(n-i),1} \in \Sigma \vee \exists k \in [n] : \text{TX}_{(i-1)+\frac{2}{n-1}(n-i),2,k} \in \Sigma)$ 
then // we are an endpoint and our counterparty has closed – 1st subscript of
TX is 2 if  $i = 1$  and  $n - 1$  if  $i = n$ 

```

```

13:   ignore all messages except for (CHECK IF CLOSING) and (FORCECLOSE) by
       $R$ 
14:    $State \leftarrow \text{CLOSING}$ 
15:   give up execution token // control goes to  $\mathcal{E}$ 
16: end if
17: let  $TX_p$  be the unique transaction among  $TX_{i,1}, (TX_{i,2,k})_{k \in [n]},$ 
       $(TX_{i,3,k_1,k_2})_{k_1,k_2 \in [n]}$  that can be appended to  $\Sigma$  in a valid way // ignore
      invalid subscript combinations
18: let sigs be the set of stored signatures that sign  $TX_p$ 
19: add  $\text{SIGN}(TX_p, sk_{i,\text{left},\text{fund},\text{old}}, \text{ANYPREVOUT}), \text{SIGN}(TX_p, sk_{i,\text{right},\text{fund},\text{old}},$ 
       $\text{ANYPREVOUT}), (\text{SIGN}(TX_p, sk_{i,j,k}, \text{ANYPREVOUT}))_{j,k \in [n]}$  to sigs // ignore invalid
      signatures
20: ignore all messages except for (CHECK IF CLOSING) by  $R$ 
21:  $State \leftarrow \text{CLOSING}$ 
22: send (SUBMIT,  $TX_p$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$ 

```

Fig. 61.

Process VIRT – On input (CHECK IF CLOSING) by R :

```

1: ensure  $State = \text{CLOSING}$ 
2: ensure  $R \in \{\text{guest}, \text{funder}, \text{fundee}\}$ 
3: send (READ) to  $\mathcal{G}_{\text{Ledger}}$  as  $R$  and assign reply to  $\Sigma$ 
4: if  $i = 1$  then // we are host_funder
5:   ensure that there exists an output with  $c_P + c_{\bar{P}} - c_{\text{virt}}$  coins and a
       $2/\{pk_{1,\text{fund},\text{new}}, pk_{2,\text{fund},\text{new}}\}$  spending method with expired/non-existent
      timelock in  $\Sigma$  // new base funding output
6:   ensure that there either exists an output with  $c_{\text{virt}}$  coins and a
       $2/\{pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}}\}$  spending method with expired/non-existent timelock
      in  $\Sigma$  /*virtual funding output by a “bridge” tx*/ or a bridgep output. In the
      latter case, collect all  $B_p$ ’s signatures in sigs, add  $\text{SIGN}(B_p, sk_{1,2,1},$ 
       $\text{ANYPREVOUT})$  (or, if  $p = n, 1$ ,  $\text{SIGN}(B_p, sk_{1,n-1,n}, \text{ANYPREVOUT})$  instead) to sigs,
      send (SUBMIT,  $B_p$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$  and keep waiting here for (CHECK IF
      CLOSING) by  $R$  until  $B_p$  is in  $\Sigma$  returned by sending (READ) to  $\mathcal{G}_{\text{Ledger}}$ .
7: else if  $i = n$  then // we are host_fundee
8:   ensure that there exists an output with  $c_P + c_{\bar{P}} - c_{\text{virt}}$  coins and a
       $2/\{pk_{n-1,\text{fund},\text{new}}, pk_{n,\text{fund},\text{new}}\}$  spending method with expired/non-existent
      timelock in  $\Sigma$  // new base funding output
9:   ensure that there either exists an output with  $c_{\text{virt}}$  coins and a
       $2/\{pk_{\text{left},\text{virt}}, pk_{\text{right},\text{virt}}\}$  spending method with expired/non-existent timelock
      in  $\Sigma$  /*virtual funding output by a “bridge” tx*/ or a bridgep output. In the
      latter case, collect all  $B_p$ ’s signatures in sigs, add  $\text{SIGN}(B_p, sk_{1,2,1},$ 
       $\text{ANYPREVOUT})$  (or, if  $p = n, 1$ ,  $\text{SIGN}(B_p, sk_{1,n-1,n}, \text{ANYPREVOUT})$  instead) to sigs,
      send (SUBMIT,  $B_p$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$  and keep waiting here for (CHECK IF
      CLOSING) by  $R$  until  $B_p$  is in  $\Sigma$  returned by sending (READ) to  $\mathcal{G}_{\text{Ledger}}$ .

```

```

10: else // we are intermediary
11:   if side = "left" then  $j \leftarrow i - 1$  else  $j \leftarrow i + 1$  // side is defined for all
      intermediaries – c.f. Fig. 49, l. 11
12:   ensure that there exists an output with  $c_P + c_{\bar{P}} - c_{\text{virt}}$  coins and a
       $2/\{pk_{i,\text{fund,new}}, pk_{j,\text{fund,new}}\}$  spending method with expired/non-existent
      timelock in  $\Sigma$ 
13:   ensure that there either exists an output with  $c_{\text{virt}}$  coins and a  $pk_{i,\text{out}}$ 
      spending method with expired/non-existent timelock in  $\Sigma$  /*virtual funding
      output by a "bridge" tx*/ or a  $\text{bridge}_{i-1,p}$  output. In the latter case, collect
      all  $B_{i-1,p}$ 's signatures in sigs, add  $\text{SIGN}(B_{i-1,p}, sk_{1,2,1}, \text{ANYPREVOUT})$  (or, if
       $i - 1, p = n, 1$ ,  $\text{SIGN}(B_{i-1,p}, sk_{1,n-1,n}, \text{ANYPREVOUT})$  instead) to sigs, send
      (SUBMIT,  $B_{i-1,p}$ , sigs) to  $\mathcal{G}_{\text{Ledger}}$  and keep waiting here for (CHECK IF
      CLOSING) by  $R$  until  $B_{i-1,p}$  is in  $\Sigma$  returned by sending (READ) to  $\mathcal{G}_{\text{Ledger}}$ .
14: end if
15:  $State \leftarrow \text{CLOSED}$ 
16: output (CLOSED) to  $R$ 

```

Fig. 62.

Process VIRT – On (COOP CLOSE, sig_bal, left_comms_revkeys) by \bar{P} :

```

// we are left intermediary or host of fundee
1: ensure  $State = \text{OPEN}$ 
2: parse sig_bal as  $(c'_1, c'_2), \text{sig}_1, \text{sig}_2$ 
3: ensure  $c_{\text{virt}} = c'_1 + c'_2$ 
4: ensure  $\text{VERIFY}((c'_1, c'_2), \text{sig}_1, pk_{\text{left,virt}}) = \text{True}$ 
5: ensure  $\text{VERIFY}((c'_1, c'_2), \text{sig}_2, pk_{\text{right,virt}}) = \text{True}$ 
6:  $State \leftarrow \text{COOP CLOSING}$ 
7: extract  $\text{sig}_{i-1,\text{right},C}, pk_{i-1,\text{right},R}$  from left_comms_revkeys
8: if  $i < n$  then  $M \leftarrow \text{CHECK COOP CLOSE}$  else
    $M \leftarrow \text{CHECK COOP CLOSE FUNDEE}$ 
9: output  $(M, (c'_1, c'_2), \text{sig}_{i-1,\text{right},C}, pk_{i-1,\text{right},R})$  to guest
10: ensure  $State = \text{OPEN}$  // executed by guest
11:  $State \leftarrow \text{COOP CLOSING}$ 
12: store received signature as  $\text{sig}_{\bar{P},C,i+1}$  // in guests,  $i$  is the current state
    number
13: store received revocation key as  $pk_{\bar{P},R,i+2}$ 
14: remove most recent keys from list of old funding keys and assign them to
     $sk'_{P,F}, pk'_{P,F}$  and  $pk'_{\bar{P},F}$ 
15:  $C_{P,i+1} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}} + c'_1 + c'_2, 2/\{pk'_{P,F}, pk'_{\bar{P},F}\})$ , outputs:
     $(c_P + c'_2, (pk_{P,\text{out}} + (p + s)) \vee 2/\{pk_{\bar{P},R,i+1}, pk_{P,R,i+1}\})$ ,  $(c_{\bar{P}} + c'_1, pk_{\bar{P},\text{out}})$ }
16: ensure  $\text{VERIFY}(C_{P,i+1}, \text{sig}_{\bar{P},C,i+1}, pk'_{\bar{P},F}) = \text{True}$ 
17: input (COOP CLOSE CHECK OK) to hostP
18: if  $i < n$  then // we are intermediary
19:   input (COOP CLOSE, left_comms_keys) to sibling

```



```

20:   ensure  $State = \text{OPEN}$  // executed by sibling
21:    $State \leftarrow \text{COOP CLOSING}$ 
22:   output (COOP CLOSE SIGN COMM,  $(c'_1, c'_2)$ ) to guest
23:   ensure  $State = \text{OPEN}$  // executed by guest of sibling
24:    $State \leftarrow \text{COOP CLOSING}$ 
25:   remove most recent keys from list of old funding keys and assign them to
    $sk'_{P,F}$ ,  $pk'_{P,F}$  and  $pk'_{\bar{P},F}$ 
26:    $C_{\bar{P},i+1} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}} + c'_1 + c'_2, 2/\{pk'_{P,F}, pk'_{\bar{P},F}\})$ , outputs:
    $(c_P + c'_1, pk_{P,\text{out}})$ ,  $(c_{\bar{P}} + c'_2, (pk_{\bar{P},\text{out}} + (p + s)) \vee 2/\{pk_{P,R,i+1}, pk_{\bar{P},R,i+1}\})$ }
27:    $\text{sig}_{P,C,i+1} \leftarrow \text{SIGN}(C_{\bar{P},i+1}, sk'_{P,F})$ 
28:    $(sk_{P,R,i+2}, pk_{P,R,i+2}) \leftarrow \text{KEYGEN}()$ 
29:   input (NEW COMM TX,  $\text{sig}_{P,C,i+1}$ ,  $pk_{P,R,i+2}$ ) to  $\text{host}_P$ 
30:   rename received signature to  $\text{sig}_{i,\text{right},C}$  // executed by sibling
31:   rename received public key to  $pk_{i,\text{right},R}$  // in hosts,  $i$  is our hop number
32:   send (COOP CLOSE,  $\text{sig\_bal}$ , ( $\text{left\_comms\_keys}$ ,  $\text{sig}_{i,\text{right},C}$ ,  $pk_{i,\text{right},R}$ ) to
    $\bar{P}$  and expect reply (COOP CLOSE BACK, ( $\text{right\_comms\_revkeys}$ ,
    $\text{right\_revocations}$ ))
33:    $R_{\text{loc},\text{right},\text{virt}} \leftarrow \text{TX}$  {input:  $(c_{\text{virt}}, 2/\{pk_{i,\text{rev}}, pk_{i+1,\text{rev}}\})$ , output:
    $(c_{\text{virt}}, pk_{i,\text{out}})$ }
34:   extract  $\text{sig}_{i+1,\text{right},\text{rev},\text{virt}}$  from  $\text{right\_revocations}$ 
35:   ensure  $\text{VERIFY}(R_{\text{loc},\text{right},\text{virt}}, \text{sig}_{i+1,\text{right},\text{rev},\text{virt}}, pk_{i+1,\text{rev}}) = \text{True}$ 
36:    $R_{\text{loc},\text{right},\text{fund}} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}}, 2/\{pk_{i,\text{rev}}, pk_{i+1,\text{rev}}\})$ , output:
    $(c_P + c_{\bar{P}}, pk_{i,\text{out}})$ }
37:   extract  $\text{sig}_{i+1,\text{right},\text{rev},\text{fund}}$  from  $\text{right\_revocations}$ 
38:   ensure  $\text{VERIFY}(R_{\text{loc},\text{right},\text{fund}}, \text{sig}_{i+1,\text{right},\text{rev},\text{fund}}, pk_{i+1,\text{rev}}) = \text{True}$ 
39:   extract  $\text{sig}_{i+1,\text{left},C}$  from  $\text{right\_comms\_revkeys}$ 
40:   extract  $\text{sig}_{i+1,\text{left},R}$  from  $\text{right\_revocations}$ 
41:   extract  $pk_{i+1,\text{left},R}$  from  $\text{right\_comms\_revkeys}$ 
42:   output (VERIFY COMM REV,  $\text{sig}_{i+1,\text{left},C}$ ,  $\text{sig}_{i+1,\text{left},R}$ ,  $pk_{i+1,\text{left},R}$ ) to guest
43:   store received public key as  $pk_{\bar{P},R,i+2}$  // executed by guest of sibling
44:   store  $\text{sig}_{i+1,\text{left},C}$  as  $\text{sig}_{\bar{P},C,i+1}$ ,  $pk_{\bar{P},R,i+2}$ 
45:    $C_{P,i+1} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}} + c'_1 + c'_2, 2/\{pk'_{P,F}, pk'_{\bar{P},F}\})$ , outputs:
    $(c_P + c_1, (pk_{P,\text{out}} + (p + s)) \vee 2/\{pk_{P,R,i+1}, pk_{\bar{P},R,i+1}\})$ ,  $(c_{\bar{P}} + c'_2, pk_{\bar{P},\text{out}})$ }
46:   ensure  $\text{VERIFY}(C_{P,i+1}, \text{sig}_{\bar{P},C,i+1}, pk'_{\bar{P},F}) = \text{True}$ 
47:   store  $\text{sig}_{i+1,\text{left},R}$  as  $\text{sig}_{\bar{P},R,i}$ 
48:    $R_{P,i} \leftarrow \text{TX}$  {input:  $C_{\bar{P},i}$ .outputs. $\bar{P}$ , output:  $(c_P + c_{\bar{P}}, pk_{P,\text{out}})$ }
49:   ensure  $\text{VERIFY}(R_{P,i}, \text{sig}_{\bar{P},R,i}, pk_{\bar{P},R,i}) = \text{True}$ 
50:   input (COMM REV VERIFIED) to  $\text{host}_P$ 
51:   output (COOP CLOSE BACK,  $\text{right\_comms\_revkeys}$ ,  $\text{right\_revocations}$ )
   to sibling // executed by sibling
52:    $R_{\text{loc},\text{left},\text{virt}} \leftarrow \text{TX}$  {input:  $(c_{\text{virt}}, 4/\{pk_{1,\text{rev}}, pk_{i-1,\text{rev}}, pk_{i,\text{rev}}, pk_{n,\text{rev}}\})$ ,
   output:  $(c_{\text{virt}}, pk_{i,\text{out}})$ } // the input corresponds to the revocation path of the
   virtual output of all virtual txs owned by  $\bar{P}$ 
53:   extract  $\text{sig}_{n,i,\text{left},\text{rev},\text{virt}}$  from  $\text{right\_revocations}$ 
54:   ensure  $\text{VERIFY}(R_{\text{loc},\text{left}}, \text{sig}_{n,i,\text{left},\text{rev}}, pk_{n,\text{rev}}) = \text{True}$ 
55:   if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
56:   if  $i = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 

```

```

57:   ensure that the following signatures are present in right_revocations and
      store them:
      - // 1 signature
58:       sig( $R_{i-1,1}, pk_{n,rev}$ )
      - //  $l - m$  signatures
59:        $\forall k \in \{m, \dots, l\} \setminus \{i\} :$ 
60:       sig( $R_{i-1,2,k}, pk_{n,rev}$ )
      - //  $(i - m) \cdot (l - i)$  signatures
61:        $\forall k_1 \in \{m, \dots, i - 1\}, \forall k_2 \in \{i + 1, \dots, l\} :$ 
62:       sig( $R_{i-1,3,k_1,k_2}, pk_{n,rev}$ )
63: else //  $i = n$ , we are host of fundee
64:   output (REVOKE) to fundee
65:    $R_{\bar{P},i} \leftarrow \text{TX}$  {input:  $C_{P,i}.\text{outputs}.P$ , output:  $(c_P, pk_{\bar{P},out})$ } // executed by
      fundee
66:    $\text{sig}_{P,R,i} \leftarrow \text{SIGN}(R_{\bar{P},i}, sk_{P,R,i})$ 
67:   virtual_revocation_sigs  $\leftarrow \emptyset$ 
68:   for  $j \in [n - 1]$  do
69:      $R_{j,1} \leftarrow \text{TX}$  {input:  $\text{TX}_{j,1}.\text{revocation}_1$ , output:  $(c_{virt}, pk_{j+1,out})$ }
70:      $\text{sig}_{j,R,1,i} \leftarrow \text{SIGN}(R_{j,1}, sk_{i,rev})$ ;
     virtual_revocation_sigs  $\leftarrow \text{virtual_revocation_sigs} \cup \text{sig}_{j,R,1,i}$ 
71:     if  $j = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
72:     if  $j = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 
73:     for  $k \in \{m, \dots, l\}$  do
74:        $R_{j,2,k} \leftarrow \text{TX}$  {input:  $\text{TX}_{j,2,k}.\text{revocation}_{2,k}$ , output:
          $(c_{virt}, pk_{j+1,out})$ }
75:        $\text{sig}_{j,R,2,k,i} \leftarrow \text{SIGN}(R_{j,2,k}, sk_{i,rev})$ ;
       virtual_revocation_sigs  $\leftarrow \text{virtual_revocation_sigs} \cup \text{sig}_{j,R,2,k,i}$ 
76:     end for
77:     for  $k_1 \in \{m, \dots, j - 1\}, k_2 \in \{j + 1, \dots, l\}$  do
78:        $R_{j,3,k_1,k_2} \leftarrow \text{TX}$  {input:  $\text{TX}_{j,3,k_1,k_2}.\text{revocation}_{3,k_1,k_2}$ , output:
          $(c_{virt}, pk_{j+1,out})$ }
79:        $\text{sig}_{j,R,3,k_1,k_2,i} \leftarrow \text{SIGN}(R_{j,3,k_1,k_2}, sk_{i,rev})$ ;
       virtual_revocation_sigs  $\leftarrow \text{virtual_revocation_sigs} \cup \text{sig}_{j,R,3,k_1,k_2,i}$ 
80:     end for
81:   end for
82:   input (REVOCATIONS,  $\text{sig}_{P,R,i}$ , virtual_revocation_sigs) to hostP
83:   rename received signature  $\text{sig}_{P,R,i}$  to  $\text{sig}_{n,right,R}$ 
84:   for all  $j \in \{2, \dots, n\}$  do
85:      $R_{j,left} \leftarrow \text{TX}$  {input:  $(c_{virt}, 4/\{pk_{1,rev}, pk_{j-1,rev}, pk_{j,rev}, pk_{n,rev}\})$ ,
      output:  $(c_{virt}, pk_{j,out})$ }
86:      $\text{sig}_{n,j,left,rev} \leftarrow \text{SIGN}(R_{j,left}, sk_{n,rev})$ 
87:   end for
88: end if
89: output (NEW COMM REV) to guest

```

```

90:  $C_{\bar{P},i+1} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}} + c'_1 + c'_2, 2/\{pk'_{\bar{P},F}, pk'_{P,F}\})$ , outputs:
     $(c_{\bar{P}} + c'_1, (pk_{\bar{P},\text{out}} + (p + s)) \vee 2/\{pk_{\bar{P},R,i+1}, pk_{P,R,i+1}\})$ ,  $(c_P + c'_2, pk_{P,\text{out}})$ } //
    executed by guest
91:  $\text{sig}_{P,C,i+1} \leftarrow \text{SIGN}(C_{\bar{P},i+1}, sk'_{P,F})$ 
92:  $R_{\bar{P},i} \leftarrow \text{TX}$  {input:  $C_{P,i}.\text{outputs}.P$ , output:  $(c_P + c_{\bar{P}}, pk_{\bar{P},\text{out}})$ }
93:  $\text{sig}_{P,R,i} \leftarrow \text{SIGN}(R_{\bar{P},i}, sk_{P,R,i})$ 
94:  $(sk_{P,R,i+2}, pk_{P,R,i+2}) \leftarrow \text{KEYGEN}()$ 
95: input (NEW COMM REV,  $\text{sig}_{P,C,i+1}$ ,  $\text{sig}_{P,R,i}$ ,  $pk_{P,R,i+2}$ ) to host $_P$ 
96: rename  $\text{sig}_{P,C,i+1}$  to  $\text{sig}_{i,\text{left},C}$ 
97: rename  $\text{sig}_{P,R,i}$  to  $\text{sig}_{i,\text{left},R}$ 
98: rename received public key to  $pk_{i,\text{left},R}$ 
99:  $R_{\text{rem},\text{left},\text{virt}} \leftarrow \text{TX}$  {input:  $(c_{\text{virt}}, 2/\{pk_{i-1,\text{rev}}, pk_{i,\text{rev}}\})$ , output:
     $(c_{\text{virt}}, pk_{i-1,\text{out}})$ }
100:  $\text{sig}_{i,\text{left},\text{rev},\text{virt}} \leftarrow \text{SIGN}(R_{\text{rem},\text{left},\text{virt}}, sk_{i,\text{rev}})$ 
101:  $R_{\text{rem},\text{left},\text{fund}} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}}, 2/\{pk_{i-1,\text{rev}}, pk_{i,\text{rev}}\})$ , output:
     $(c_P + c_{\bar{P}}, pk_{i-1,\text{out}})$ }
102:  $\text{sig}_{i,\text{left},\text{rev},\text{fund}} \leftarrow \text{SIGN}(R_{\text{rem},\text{left},\text{fund}}, sk_{i,\text{rev}})$ 
103: if  $i < n$  then // we are intermediary
104:    $M \leftarrow (\text{COOP CLOSE BACK}, ((\text{right\_comms\_revkeys}, \text{sig}_{i,\text{left},C}, pk_{i,\text{left},R}),$ 
     $(\text{right\_revocations}, \text{sig}_{i,\text{left},\text{rev},\text{virt}}, \text{sig}_{i,\text{left},\text{rev},\text{fund}}, \text{sig}_{i,\text{left},R})))$ 
105: else //  $i = n$ , we are host of fundee
106:    $M \leftarrow (\text{COOP CLOSE BACK}, (\text{sig}_{i,\text{left},C}, pk_{i,\text{left},R}, \text{sig}_{n,\text{left},R}), (\text{sig}_{n,\text{left},\text{rev},\text{virt}},$ 
     $\text{sig}_{n,\text{left},\text{rev},\text{fund}}, (\text{sig}_{n,j,\text{left},\text{rev}})_{j \in \{2, \dots, n\}}, \text{virtual\_rev\_sigs}))$ 
107: end if
108: send  $M$  to  $\bar{P}$  and expect reply (COOP CLOSE REVOCATIONS,
    left_revocations)
109: extract  $\text{sig}_{i-1,\text{right},R}$ ,  $\text{sig}_{1,i,\text{right},\text{rev}}$ ,  $\text{sig}_{i-1,\text{right},\text{rev}}$  from left_revocations
110: ensure  $\text{VERIFY}(R_{\text{loc},\text{left},\text{virt}}, \text{sig}_{1,\text{right},\text{rev}}, pk_{1,\text{rev}}) = \text{True}$ 
111: ensure  $\text{VERIFY}(R_{\text{loc},\text{left},\text{virt}}, \text{sig}_{i-1,\text{right},\text{rev}}, pk_{i-1,\text{rev}}) = \text{True}$ 
112:  $R_{\text{loc},\text{left},\text{fund}} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}}, 2/\{pk_{i-1,\text{rev}}, pk_{i,\text{rev}}\})$ , output:
     $(c_P + c_{\bar{P}}, pk_{i,\text{out}})$ } // the input corresponds to the revocation path of the right
    funding output of all virtual txs owned by  $\bar{P}$ 
113: extract  $\text{sig}_{i-1,\text{left},\text{rev},\text{fund}}$  from left_revocations
114: ensure  $\text{VERIFY}(R_{\text{loc},\text{left},\text{fund}}, \text{sig}_{i-1,\text{left},\text{rev},\text{fund}}, pk_{i-1,\text{rev}}) = \text{True}$ 
115: if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
116: if  $i = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 
117: ensure that the following signatures are present in left_revocations and
    store them:
    - // 2 signatures
118:    $\text{sig}(R_{i-1,1}, pk_{1,\text{rev}}), \text{sig}(R_{i-1,1}, pk_{i-1,\text{rev}})$ 
    - //  $2(l - m)$  signatures
119:    $\forall k \in \{m, \dots, l\} \setminus \{i\}$ :
120:      $\text{sig}(R_{i-1,2,k}, pk_{1,\text{rev}}), \text{sig}(R_{i-1,2,k}, pk_{i-1,\text{rev}})$ 
    - //  $2(i - m) \cdot (l - i)$  signatures
121:    $\forall k_1 \in \{m, \dots, i - 1\}, \forall k_2 \in \{i + 1, \dots, l\}$ :
122:      $\text{sig}(R_{i-1,3,k_1,k_2}, pk_{1,\text{rev}}), \text{sig}(R_{i-1,3,k_1,k_2}, pk_{i-1,\text{rev}})$ 

```

```

123: output (VERIFY REV,  $\text{sig}_{i-1, \text{right}, R}$ ,  $\text{host}_P$ ) to guest
124: store received signature as  $\text{sig}_{\text{bar } P, R, i}$  // executed by guest
125:  $R_{P, i} \leftarrow \text{TX}$  {input:  $C_{\bar{P}, i}.\text{outputs}.\bar{P}$ , output:  $(c_P + c_{\bar{P}}, pk_{P, \text{out}})$ }
126: ensure  $\text{VERIFY}(R_{P, i}, \text{sig}_{\bar{P}, R, i}, pk_{\bar{P}, R, i}) = \text{True}$ 
127: add  $\text{host}_P$  to list of old hosts
128: assign received host to  $\text{host}_P$ 
129:  $i \leftarrow i + 1$ ;  $c_P \leftarrow c_P + c'_2$ ;  $c_{\bar{P}} \leftarrow c_{\bar{P}} + c'_1$ 
130: add  $sk_{P, F}, pk_{P, F}, pk_{\bar{P}, F}$  to list of old enabler channel funding keys
131:  $(sk_{P, F}, pk_{P, F}) \leftarrow (sk'_{P, F}, pk'_{P, F})$ 
132:  $\text{layer} \leftarrow \text{layer} - 1$ 
133:  $\text{locked}_P \leftarrow \text{locked}_P - c_{\text{virt}}$ 
134:  $\text{State} \leftarrow \text{OPEN}$ 
135:  $\text{hosting} \leftarrow \text{False}$ 
136: input (REV VERIFIED) to last old host
137:  $\text{State} \leftarrow \text{COOP CLOSED}$ 
138: if  $i < n$  then // we are intermediary
139:   send (COOP CLOSE REVOCATIONS,  $\text{left\_revocations}$ ) to sibling
140:   output (COOP CLOSE REVOCATIONS,  $\text{host}_P$ ) to guest // executed by
   sibling
141:  $R_{\bar{P}, i} \leftarrow \text{TX}$  {input:  $C_{P, i}.\text{outputs}.P$ , output:  $(c_P, pk_{\bar{P}, \text{out}})$ } // executed by
   guest of sibling
142:  $\text{sig}_{P, R, i} \leftarrow \text{SIGN}(R_{\bar{P}, i}, sk_{P, R, i})$ 
143: add  $\text{host}_P$  to list of old hosts
144: assign received host to  $\text{host}_P$ 
145:  $i \leftarrow i + 1$ ;  $c_P \leftarrow c_P + c'_1$ ;  $c_{\bar{P}} \leftarrow c_{\bar{P}} + c'_2$ 
146: add  $sk_{P, F}, pk_{P, F}, pk_{\bar{P}, F}$  to list of old enabler channel funding keys
147:  $(sk_{P, F}, pk_{P, F}) \leftarrow (sk'_{P, F}, pk'_{P, F})$ 
148:  $\text{layer} \leftarrow \text{layer} - 1$ 
149:  $\text{locked}_P \leftarrow \text{locked}_P - c_{\text{virt}}$ 
150:  $\text{State} \leftarrow \text{OPEN}$ 
151:  $\text{hosting} \leftarrow \text{False}$ 
152: input (REVOCATION,  $\text{sig}_{P, R, i}$ ) to last old host
153: rename received signature to  $\text{sig}_{i, \text{right}, R}$  // executed by sibling
154:  $R_{\text{rem}, \text{right}, \text{virt}} \leftarrow \text{TX}$  {input:  $(c_{\text{virt}}, 4/\{pk_{1, \text{rev}}, pk_{i, \text{rev}}, pk_{i+1, \text{rev}}, pk_{n, \text{rev}}\})$ ,
   output:  $(c_{\text{virt}}, pk_{i+1, \text{out}})$ }
155:  $\text{sig}_{i, \text{right}, \text{rev}, \text{virt}} \leftarrow \text{SIGN}(R_{\text{rem}, \text{right}, \text{virt}}, sk_{i, \text{rev}})$ 
156:  $R_{\text{rem}, \text{right}, \text{fund}} \leftarrow \text{TX}$  {input:  $(c_P + c_{\bar{P}}, 2/\{pk_{i, \text{rev}}, pk_{i+1, \text{rev}}\})$ , output:
    $(c_P + c_{\bar{P}}, pk_{i+1, \text{out}})$ }
157:  $\text{sig}_{i, \text{right}, \text{rev}, \text{fund}} \leftarrow \text{SIGN}(R_{\text{rem}, \text{right}, \text{fund}}, sk_{i, \text{rev}})$ 
158:  $R_{i, 1} \leftarrow \text{TX}$  {input:  $\text{TX}_{i, 1}.\text{revocation}_1$ , output:  $(c_{\text{virt}}, pk_{i+1, \text{out}})$ }
159:  $\text{sig}_{i, R, 1, i} \leftarrow \text{SIGN}(R_{i, 1}, sk_{i, \text{rev}})$ ;
    $\text{left\_revocations} \leftarrow \text{left\_revocations} \cup \text{sig}_{i, R, 1, i}$ 
160: if  $i = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
161: if  $i = n - 1$  then  $l \leftarrow n$  else  $l \leftarrow n - 1$ 
162: for  $k \in \{m, \dots, l\}$  do
163:    $R_{i, 2, k} \leftarrow \text{TX}$  {input:  $\text{TX}_{i, 2, k}.\text{revocation}_{2, k}$ , output:  $(c_{\text{virt}}, pk_{i+1, \text{out}})$ }

```

```

164:    $\text{sig}_{i,R,2,k,i} \leftarrow \text{SIGN}(R_{i,2,k}, sk_{i,\text{rev}});$ 
       $\text{left\_revocations} \leftarrow \text{left\_revocations} \cup \text{sig}_{i,R,2,k,i}$ 
165:   end for
166:   for  $k_1 \in \{m, \dots, i-1\}, k_2 \in \{i+1, \dots, l\}$  do
167:      $R_{i,3,k_1,k_2} \leftarrow \text{TX} \{ \text{input: } \text{TX}_{i,3,k_1,k_2}.\text{revocation}_{3,k_1,k_2}, \text{output:}$ 
       $(c_{\text{virt}}, pk_{i+1,\text{out}}) \}$ 
168:      $\text{sig}_{i,R,3,k_1,k_2,i} \leftarrow \text{SIGN}(R_{i,3,k_1,k_2}, sk_{i,\text{rev}});$ 
       $\text{left\_revocations} \leftarrow \text{left\_revocations} \cup \text{sig}_{i,R,3,k_1,k_2,i}$ 
169:   end for
170:   send (COOP CLOSE REVOCATIONS, ( $\text{left\_revocations}$ ,  $\text{sig}_{i,\text{right},R}$ ,
       $\text{sig}_{i,\text{right},\text{rev},\text{virt}}$ ,  $\text{sig}_{i,\text{right},\text{rev},\text{fund}}$ ) to  $\bar{P}$ )
171: else //  $i = n$ , we are host of fundee
172:   extract  $\text{sig}_{1,\text{right},R}$  from  $\text{left\_revocations}$ 
173:   output (VERIFY REVOCATION,  $\text{sig}_{1,\text{right},R}$ ) to fundee
174:   store received signature as  $\text{sig}_{\bar{P},R,i}$  // executed by fundee
175:    $R_{P,i} \leftarrow \text{TX} \{ \text{input: } C_{\bar{P},i}.\text{outputs}.\bar{P}, \text{output: } (c_{\bar{P}}, pk_{P,\text{out}}) \}$ 
176:   ensure  $\text{VERIFY}(R_{P,i}, \text{sig}_{\bar{P},R,i}, pk_{\bar{P},R,i}) = \text{True}$ 
177:   for  $j \in [n-1]$  do
178:     if  $j = 2$  then  $m \leftarrow 1$  else  $m \leftarrow 2$ 
179:     if  $j = n-1$  then  $l \leftarrow n$  else  $l \leftarrow n-1$ 
180:     ensure that the following signatures are present in  $\text{left\_revocations}$ 
      and store them: // exclude signatures by  $j+1$  if  $j = n-1$ 
      - // 3 signatures
181:      $\text{sig}(R_{j,1}, pk_{1,\text{rev}}), \text{sig}(R_{j,1}, pk_{j,\text{rev}}), \text{sig}(R_{j,1}, pk_{j+1,\text{rev}})$ 
      - //  $3(l-m)$  signatures
182:      $\forall k \in \{m, \dots, l\} \setminus \{i\} :$ 
183:      $\text{sig}(R_{j,2,k}, pk_{1,\text{rev}}), \text{sig}(R_{j,2,k}, pk_{j,\text{rev}}), \text{sig}(R_{j,2,k}, pk_{j+1,\text{rev}})$ 
      - //  $3(i-m) \cdot (l-i)$  signatures
184:      $\forall k_1 \in \{m, \dots, i-1\}, \forall k_2 \in \{i+1, \dots, l\} :$ 
185:      $\text{sig}(R_{j,3,k_1,k_2}, pk_{1,\text{rev}}), \text{sig}(R_{j,3,k_1,k_2}, pk_{j,\text{rev}}),$ 
       $\text{sig}(R_{j,3,k_1,k_2}, pk_{j+1,\text{rev}})$ 
186:   end for
187:    $\text{State} \leftarrow \text{COOP CLOSED}$ 
188:   if  $\text{close\_initiator} = P$  then //  $\mathcal{E}$  instructed us to close the channel
189:     execute code of Fig. 45
190:   else //  $\mathcal{E}$  instructed another party to close the channel
191:     send (COOPCLOSED) to  $\text{close\_initiator}$ 
192:   end if
193: end if

```

Fig. 63.

Process VIRT – punishment handling

```

1: On input (USED REVOCATION) by guest: // (USED REVOCATION) by
   funder/fundee is ignored
2:    $State \leftarrow$  GUEST PUNISHED
3:   input (USED REVOCATION) to  $host_P$ , expect reply (USED REVOCATION OK)
4:   if funder or fundee is defined then
5:     output (ENABLER USED REVOCATION) to it
6:   else // sibling is defined
7:     output (ENABLER USED REVOCATION) to sibling
8:   end if

9: On input (ENABLER USED REVOCATION) by sibling:
10:   $State \leftarrow$  GUEST PUNISHED
11:  output (ENABLER USED REVOCATION) to guest

12: On output (USED REVOCATION) by  $host_P$ :
13:   $State \leftarrow$  GUEST PUNISHED
14:  if funder or fundee is defined then
15:    output (ENABLER USED REVOCATION) to it
16:  else // sibling is defined
17:    output (ENABLER USED REVOCATION) to sibling
18:  end if

```

Fig. 64.

E Liveness

Proposition 1. *Consider a synchronised honest party that submits a transaction \mathbf{tx} to the ledger functionality [10] by the time the block indexed by h is added to **state** in its view. Then \mathbf{tx} is guaranteed to be included in the block range $[h + 1, h + s]$, where $s = (2 + q)windowSize$ and $q = \lceil (maxTime_{window} + \frac{Delay}{2}) / minTime_{window} \rceil$.*

The proof can be found in [34].

F Omitted Proofs

Lemma 4 (Real world balance security). *Consider a real world execution with $P \in \{Alice, Bob\}$ honest LN ITI and \bar{P} the counterparty ITI. Assume that all of the following are true:*

- the internal variable **negligent** of P has value “False”,
- P has transitioned to the OPEN State for the first time after having received (OPEN, c, \dots) by either \mathcal{E} or \bar{P} ,
- P [has received (FUND ME, f_i, \dots) as input by another LN ITI while State was OPEN and subsequently P transitioned to OPEN State] n times,
- P [has received (CHECK COOP CLOSE FUNDEE, ($_, r_i$), \dots) as output by host_P while State was OPEN and subsequently P transitioned to OPEN State] j times,
- P [has received (COOP CLOSE SIGN COMM FUNDER, ($l_i, _$)) as output by host_P while State was OPEN and subsequently P transitioned to OPEN State] k times,
- P [has received (PAY, d_i) by \mathcal{E} while State was OPEN and P subsequently transitioned to OPEN State] m times,
- P [has received (GET PAID, e_i) by \mathcal{E} while State was OPEN and P subsequently transitioned to OPEN State] l times.

Let $\phi = 1$ if $P = \text{Alice}$, or $\phi = 0$ if $P = \text{Bob}$.

- If P receives (FORCECLOSE) by \mathcal{E} and, if $\text{host}_P \neq \text{“ledger”}$ the output of host_P is (CLOSED), then eventually the state obtained when P inputs (READ) to $\mathcal{G}_{\text{Ledger}}$ will contain h outputs each of value c_i and that has been spent or is exclusively spendable by $pk_{R,\text{out}}$ such that

$$\sum_{i=1}^h c_i \geq \phi \cdot c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^j r_i + \sum_{i=1}^k l_i \quad (3)$$

with overwhelming probability in the security parameter, where R is a local, kindred LN machine (i.e. either P , the **guest** of host_P ’s **sibling**, the party to which P sent FUND ME if such a message has been sent, or the **guest** of the **sibling** of one of the transitive closure of hosts of P).

- Assume that, at some particular instant during the execution,
 1. $\text{host}_P \neq \text{“ledger”}$,
 2. P has State OPEN.

Consider two alternative series of subsequent execution steps:

1. The **guest** of host_P (call them S) receives (FORCECLOSE) by \mathcal{E} . From that point onward, all protocol parties (even corrupted ones) honestly follow the protocol. Eventually a total of c_b coins is exclusively spendable by $pk_{R,\text{out}}$, where R is a machine kindred to S . Additionally, there is at least one funding output of P ’s channel ($c_P + c_{\bar{P}}, 2/\{pk_{P,F}, pk_{\bar{P},F}\}$) that is on-chain and unspent.
2. P receives either (COOPCLOSE) by \mathcal{E} or (COOP CLOSE, \dots) by some other ITI, and P ’s variable **hosting** is False. Subsequently, P ’s State transitions to COOP CLOSED and then the State of S transitions to OPEN. The next time S is activated is via a (FORCECLOSE) input by \mathcal{E} and eventually a total of c_t coins is exclusively spendable by $pk_{R,\text{out}}$.

It then holds that

$$c_t - c_b \geq \phi \cdot c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^j r_i + \sum_{i=1}^k l_i \quad (4)$$

with overwhelming probability in the security parameter.

Proof (Proof of Lemma 4). We first note that, as signature forgeries only happen with negligible probability and only a polynomial number of signatures are verified by honest parties throughout an execution, the event in which any forged signature passes the verification of an honest party or of $\mathcal{G}_{\text{Ledger}}$ happens only with negligible probability. We can therefore ignore this event throughout this proof and simply add a computationally negligible distance between \mathcal{E} 's outputs in the real and the ideal world at the end.

We also note that $pk_{P,\text{out}}$ has been provided by \mathcal{E} , therefore it can freely use coins spendable by this key. This is why we allow for any of the $pk_{P,\text{out}}$ outputs to have been spent.

Define the *history* of a channel as $H = (F, C)$, where each of F, C is a list of lists of integers. A party P which satisfies the Lemma conditions has a unique, unambiguously and recursively defined history: If the value **hops** in the (OPEN, c , **hops**, ...) message was equal to "ledger", then F is the empty list, otherwise F is the concatenation of the F and C lists of the party that sent (FUNDED, ...) to P , as they were at the moment the latter message was sent. After initialised, F remains immutable. Observe that, if **hops** \neq "ledger", both aforementioned messages must have been received before P transitions to the OPEN state.

The list C of party P is initialised to $[[g]]$ when P 's *State* transitions for the first time to OPEN, where $g = c$ if $P = \text{Alice}$, or $g = 0$ if $P = \text{Bob}$; this represents the initial channel balance. The value x or $-x$ is appended to the last list in C when a payment is received (Fig. 36, l. 21) or sent (Fig. 36, l. 6) respectively by P . Moving on to the funding of new virtual channels, whenever P funds a new virtual channel (Fig. 33, l. 21), $[-c_{\text{virt}}]$ is appended to C and whenever P helps with the opening of a new virtual channel, but does not fund it (Fig. 33, l. 24), $[0]$ is appended to C . In case of cooperatively closing a channel (Figs. 44-47 & 63) to which P 's channel is base, if this channel was initially funded by P , when the closing procedure completes (Fig. 47, l. 53) $[c'_1]$ is appended to C . Likewise, if in the closed virtual channel P was the base of the **fundee** (Fig. 63, l. 171), then $[c'_2]$ (Fig. 63, l. 9) is appended to C . In case P was a left intermediary for the closed virtual channel (Fig. 63, l. 10), then $[c'_2]$ is appended to C . Lastly, in case P was a right intermediary for the closed virtual channel (Fig. 63, l. 23), then $[c'_1 - c_{\text{virt}}]$ is appended to C . Therefore C consists of one list of integers for each sequence of inbound and outbound payments that have not been interrupted by a virtualisation step and a new list is added for every virtual layer that is created or torn down cooperatively. We also observe that a non-negligent party with history (F, C) satisfies the Lemma conditions and that the value of the right hand side of the inequality (3) is equal to $\sum_{s \in C} \sum_{x \in s} x$, as all inbound and

outbound payment values, new channel funding values and cooperative closing refunds that appear in the Lemma conditions are recorded in C .

Let party P with a particular history. We will inductively prove that P satisfies the Lemma. The base case is when a channel is opened with `hops` = “ledger” and is closed right away, therefore $H = ([], [g])$, where $g = c$ if $P = \text{Alice}$ and $g = 0$ if $P = \text{Bob}$. P can transition to the OPEN *State* for the first time only if all of the following have taken place:

- It has received (OPEN, c , ...) while in the INIT *State*. In case $P = \text{Alice}$, this message must have been received as input by \mathcal{E} (Fig. 31, l. 1), or in case $P = \text{Bob}$, this message must have been received via the network by \bar{P} (Fig. 26, l. 3).
- It has received $pk_{\bar{P},F}$. In case $P = \text{Bob}$, $pk_{\bar{P},F}$ must have been contained in the (OPEN, ...) message by \bar{P} (Fig. 26, l. 3), otherwise if $P = \text{Alice}$ $pk_{\bar{P},F}$ must have been contained in the (ACCEPT CHANNEL, ...) message by \bar{P} (Fig. 26, l. 16).
- It internally holds a signature on the commitment transaction $C_{P,0}$ that is valid when verified with public key $pk_{\bar{P},F}$ (Fig. 28, ll. 12 and 23).
- It has the transaction F in the $\mathcal{G}_{\text{Ledger}}$ state (Fig. 29, l. 3 or Fig. 30, l. 16).

We observe that P satisfies the Lemma conditions with $m = n = l = 0$. Before transitioning to the OPEN *State*, P has produced only one valid signature for the “funding” output $(c, 2/\{pk_{P,F}, pk_{\bar{P},F}\})$ of F with $sk_{P,F}$, namely for $C_{\bar{P},0}$ (Fig. 28, ll. 4 or 14), and sent it to \bar{P} (Fig. 28, ll. 6 or 21), therefore the only two ways to spend $(c, 2/\{pk_{P,F}, pk_{\bar{P},F}\})$ are by either publishing $C_{P,0}$ or $C_{\bar{P},0}$. We observe that $C_{P,0}$ has a $(g, (pk_{P,\text{out}} + (t+s)) \vee 2/\{pk_{P,R}, pk_{\bar{P},R}\})$ output (Fig. 28, l. 2 or 3). The spending method $2/\{pk_{P,R}, pk_{\bar{P},R}\}$ cannot be used since P has not produced a signature for it with $sk_{P,R}$, therefore the alternative spending method, $pk_{P,\text{out}} + (t+s)$, is the only one that will be spendable if $C_{P,0}$ is included in $\mathcal{G}_{\text{Ledger}}$, thus contributing g to the sum of outputs that contribute to inequality (3). Likewise, if $C_{\bar{P},0}$ is included in $\mathcal{G}_{\text{Ledger}}$, it will contribute at least one $(g, pk_{P,\text{out}})$ output to this inequality, as $C_{\bar{P},0}$ has a $(g, pk_{P,\text{out}})$ output (Fig. 28, l. 2 or 3). Additionally, if P receives (FORCECLOSE) by \mathcal{E} while $H = ([], [g])$, it attempts to publish $C_{P,0}$ (Fig. 42, l. 19), and will either succeed or $C_{\bar{P},0}$ will be published instead. We therefore conclude that in every case $\mathcal{G}_{\text{Ledger}}$ will eventually have a state Σ that contains at least one $(g, pk_{P,\text{out}})$ output, therefore satisfying the Lemma consequence.

Let P with history $H = (F, C)$. The induction hypothesis is that the Lemma holds for P . Let c_P the sum in the right hand side of inequality (3). In order to perform the induction step, assume that P is in the OPEN state. We will prove all the following (the facts to be proven are shown with emphasis for clarity):

- If P receives (FUND ME, f , ...) by a (local, kindred) LN ITI R , subsequently transitions back to the OPEN state (therefore moving to history (F, C') where $C' = C + [-f]$) and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P before any further change to its history, then *eventually* P ’s $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i *exclusively spendable*

or already spent by $pk_{P,\text{out}}$ that are descendants of an output with spending method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ such that $\sum_{i=1}^h c_i \geq \sum_{s \in C'} \sum_{x \in s} x$. Furthermore, given that P moves to the OPEN state after the (FUND ME, ...) message, it also sends (FUNDED, ...) to R (Fig. 33, l. 22). If subsequently the state of R transitions to OPEN (therefore obtaining history (F_R, C_R) where $F_R = F + C$ and $C_R = [[f]]$), and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_R ($\text{host}_R = \text{host}_P$ – Fig. 30, l. 3) before any further change to its history, then eventually R 's $\mathcal{G}_{\text{Ledger}}$ state will contain k transaction outputs each of value c_i^R exclusively spendable or already spent by $pk_{R,\text{out}}$ that are descendants of an output with spending method $2/\{pk_{R,F}, pk_{\bar{R},F}\}$ such that $\sum_{i=1}^k c_i^R \geq \sum_{s \in C_R} \sum_{x \in s} x$.

- If P receives (VIRTUALISING, ...) by \bar{P} or **sibling**, subsequently transitions back to OPEN (therefore moving to history (F, C') where $C' = C + [0]$) and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with spending method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ such that $\sum_{i=1}^h c_i \geq \sum_{s \in C} \sum_{x \in s} x$. Furthermore, given that P moves to the OPEN state after the (VIRTUALISING, ...) message and in case it sends (FUNDED, ...) to some party R (Fig. 33, l. 19), the latter party is the (local, kindred) **fundee** of a new virtual channel. If subsequently the state of R transitions to OPEN (therefore obtaining history (F_R, C_R) where $F_R = F + C$ and $C_R = [[0]]$), and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_R ($\text{host}_R = \text{host}_P$ – Fig. 30, l. 3) before any further change to its history, then eventually R 's $\mathcal{G}_{\text{Ledger}}$ state will contain an output with a $2/\{pk_{R,F}, pk_{\bar{R},F}\}$ spending method.
- If P receives (CHECK COOP CLOSE, ...) by host_P , subsequently transitions back to OPEN (therefore moving to history (F, C') where $C' = C + [c'_2]$), and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with spending method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ such that $\sum_{i=1}^h c_i \geq \sum_{s \in C} \sum_{x \in s} x$.
- If P receives (COOP CLOSE SIGN COMM, ...) by host_P , subsequently transitions back to OPEN (therefore moving to history (F, C') where $C' = C + [c'_1 - c_{\text{virt}}]$), and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with spending

- method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ such that $\sum_{i=1}^h c_i \geq \sum_{s \in C} \sum_{x \in s} x$. Furthermore, there exists a local, kindred machine R that transitioned to the OPEN state after the last time control was obtained by one of P 's kindred machines and before P transitioned to the OPEN state, such that R obtained $c'_2 = c_{\text{virt}} - c'_1$ coins during its last activation. (In other words, P and R broke even on aggregate by first supporting the opening and then the cooperative closing of a virtual channel.)
- If P receives (COOP CLOSE SIG COMM FUNDER, ...) by host_P , subsequently transitions back to OPEN (therefore moving to history (F, C') where $C' = C + [c'_1]$) and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with spending method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ such that $\sum_{i=1}^h c_i \geq \sum_{s \in C} \sum_{x \in s} x$.
 - If P receives (CHECK COOP CLOSE FUNDEE, ...) by host_P , subsequently transitions back to OPEN (therefore moving to history (F, C') where $C' = C + [c'_2]$) and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with spending method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ such that $\sum_{i=1}^h c_i \geq \sum_{s \in C} \sum_{x \in s} x$.
 - If P receives (PAY, d) by \mathcal{E} , subsequently transitions back to OPEN (therefore moving to history (F, C') where C' is C with $-d$ appended to the last list of C) and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P (the latter only if $\text{host}_P \neq \text{"ledger"}$ or equivalently $F \neq []$) before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with a $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ spending method such that $\sum_{i=1}^h c_i \geq \sum_{s \in C'} \sum_{x \in s} x$.
 - If P receives (GET PAID, e) by \mathcal{E} , subsequently transitions back to OPEN (therefore moving to history (F, C') where C' is C with e appended to the last list of C) and finally receives (FORCECLOSE) by \mathcal{E} and (CLOSED) by host_P (the latter only if $\text{host}_P \neq \text{"ledger"}$ or equivalently $F = []$) before any further change to its history, then eventually P 's $\mathcal{G}_{\text{Ledger}}$ state will contain h transaction outputs each of value c_i exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with a $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ spending method such that $\sum_{i=1}^h c_i \geq \sum_{s \in C'} \sum_{x \in s} x$.

Consider the first bullet. By the induction hypothesis, before the funding procedure started P could close the channel and end up with on-chain transac-

tion outputs exclusively spendable or already spent by $pk_{P,\text{out}}$ with a sum value of c_P . When P is in the OPEN state and receives (FUND ME, f , ...), it can only move again to the OPEN state after doing the following state transitions: OPEN \rightarrow VIRTUALISING \rightarrow WAITING FOR REVOCATION \rightarrow WAITING FOR INBOUND REVOCATION \rightarrow WAITING FOR HOSTS READY \rightarrow OPEN. During this sequence of events, a new host_P is defined (Fig. 33, l. 6), new commitment transactions are negotiated with \bar{P} (Fig. 33, l. 9), control of the old funding output is handed over to host_P (Fig. 33, l. 11), host_P negotiates with its counterparty a new set of transactions and signatures that spend the aforementioned funding output and make available a new funding output with the keys $pk'_{P,F}, pk'_{\bar{P},F}$ as P instructed (Fig. 56 and 58) and the previous valid commitment transactions of both P and \bar{P} are invalidated (Fig. 25, l. 1 and l. 14 respectively). We note that the use of the ANYPREVOUT flag in all signatures that correspond to transaction inputs that may spend various different transaction outputs ensures that this is possible, as it avoids tying each input to a specific, predefined output. When P receives (FORCECLOSE) by \mathcal{E} , it inputs (FORCECLOSE) to host_P (Fig. 42, l. 4). As per the Lemma conditions, host_P will output (CLOSED). This can happen only when $\mathcal{G}_{\text{Ledger}}$ contains a suitable output for both P 's and R 's channel (Fig. 62, l. 5 and l. 6 respectively).

If the host of host_P is “ledger”, then the funding output $o_{1,2} = (c_P + c_{\bar{P}}, 2/\{pk_{P,F}, pk_{\bar{P},F}\})$ for the P, \bar{P} channel is already on-chain. Regarding the case in which $\text{host}_P \neq \text{“ledger”}$, after the funding procedure is complete, the new host_P will have as its host the old host_P of P . If the (FORCECLOSE) sequence is initiated, the new host_P will follow the same steps that will be described below once the old host_P succeeds in closing the lower layer (Fig. 61, l. 6). The old host_P however will see no difference in its interface compared to what would happen if P had received (FORCECLOSE) before the funding procedure, therefore it will successfully close by the induction hypothesis. Thereafter the process is identical to the one when the old $\text{host}_P = \text{“ledger”}$.

Moving on, host_P is either able to publish its $\text{TX}_{1,1}$ and $B_{1,1}$ (it has necessarily received valid signatures $\text{sig}(\text{TX}_{1,1}, pk_{\bar{P},F})$ (Fig. 58, l. 43), $\text{sig}(B_{1,1}, pk_{2,2,1})$ and $\text{sig}(B_{1,1}, pk_{n,n-1,n})$ (Fig. 56, l. 18) by its counterparty before it moved to the OPEN state for the first time), or the output $(c_P + c_{\bar{P}}, 2/\{pk_{P,F}, pk_{\bar{P},F}\})$ needed to publish $\text{TX}_{1,1}$ has already been spent. The only other transactions that can spend it are $\text{TX}_{2,1}$ and any of $(\text{TX}_{2,2,k})_{k>2}$, since these are the only transactions that spend the aforementioned output and that host_P has signed with $sk_{P,F}$ (Fig. 58, ll. 37-41). The output can be also spent by old, revoked commitment transactions, but in that case host_P would not have output (CLOSED); P would have instead detected this triggered by a (CHECK CHAIN FOR CLOSED) message by \mathcal{E} (Fig. 40) and would have moved to the CLOSED state on its own accord (lack of such a message by \mathcal{E} would lead P to become **negligent**, something that cannot happen according to the Lemma conditions). Every transaction among $\text{TX}_{1,1}, \text{TX}_{2,1}, (\text{TX}_{2,2,k})_{k>2}$ has a $(c_P + c_{\bar{P}} - f, 2/\{pk'_{P,F}, pk'_{\bar{P},F}\})$ output (Fig. 52, l. 21 and Fig. 51, ll. 41 and 128) which will end up in $\mathcal{G}_{\text{Ledger}}$ – call this output

o_P . We will prove that at most $\sum_{i=2}^{n-1} (t_i + p + s - 1)$ blocks after (FORCECLOSE) is received by P , an output o_R with c_{virt} coins and a $2/\{pk_{R,F}, pk_{\bar{R},F}\}$ spending condition without or with an expired timelock will be included in $\mathcal{G}_{\text{Ledger}}$. In case party \bar{P} is idle, then $o_{1,2}$ is consumed by $\text{TX}_{1,1}$, its virtual output is spent by $B_{1,1}$ and the timelock on the output of the latter expires, therefore the required output o_R is on-chain. In case \bar{P} is active, exactly one of $\text{TX}_{2,1}$, $(\text{TX}_{2,2,k})_{k>2}$ or $(\text{TX}_{2,3,1,k})_{k>2}$ is a descendant of $o_{1,2}$; if the transaction belongs to one of the two last transaction groups (with subscript g) then necessarily $\text{TX}_{1,1}$ is on-chain in some block height h and given the timelock on the virtual output of $\text{TX}_{1,1}$, \bar{P} 's transaction can be at most at block height $h + t_2 + p + s - 1$. If $n = 3$ or $k = n - 1$, then \bar{P} 's unique transaction has a **bridge** output which can be spent only by R_g or B_g . The P has never signed R_g , so only B_g can spend it. B_g has the required output o_R (without a timelock) and P publishes B_g (Fig. 62, l. 6). The rest of the cases are covered by the following sequence of events:

Closing sequence

- 1: $\text{maxDel} \leftarrow t_2 + p + s - 1$ // A_2 is active and the virtual output of $\text{TX}_{1,1}$ has a timelock of t_2
- 2: $i \leftarrow 3$
- 3: **loop**
- 4: **if** A_i is idle **then**
- 5: The timelock on the virtual output of the transaction published by A_{i-1} expires and therefore the required o_R is on-chain
- 6: **else** // A_i publishes a transaction that is a descendant of $o_{1,2}$
- 7: $\text{maxDel} \leftarrow \text{maxDel} + t_i + p + s - 1$
- 8: The published transaction can be of the form $\text{TX}_{i,2,2}$ or $(\text{TX}_{i,3,2,k})_{k>i}$ as it spends the virtual output which is encumbered with a public key controlled by R and R has only signed these transactions
- 9: **if** $i = n - 1$ or $k \geq n - 1$ **then** // The interval contains all intermediaries
- 10: The virtual output of the transaction is not timelocked and is only spendable by a **bridge** tx, which R publishes (Fig. 62, l. 6) and which has a $2/\{pk_{R,F}, pk_{\bar{R},F}\}$ spending method, therefore it is the required o_R
- 11: **else** // At least one intermediary is not in the interval
- 12: **if** the transaction is $\text{TX}_{i,3,2,k}$ **then** $i \leftarrow k$ **else** $i \leftarrow i + 1$
- 13: **end if**
- 14: **end if**
- 15: **end loop**
- 16: // $\text{maxDel} \leq \sum_{i=2}^{n-1} (t_i + p + s - 1)$

Fig. 65.

In every case o_P and o_R end up on-chain in at most s and $\sum_{i=2}^{n-1} (t_i + p + s - 1)$ blocks respectively from the moment (FORCECLOSE) is received. The output o_P can be spent either by $C_{P,i}$ or $C_{\bar{P},i}$. Both these transactions have a $(c_P - f, pk_{P,\text{out}})$ output. This output of $C_{P,i}$ is timelocked, but the alternative spending method cannot be used as P never signed a transaction that uses it (as it is reserved for revocation, which has not taken place yet in this virtualisation layer). We have now proven that if P completes the funding of a new channel then it can close its channel for a $(c_P - f, pk_{P,\text{out}})$ output that is a descendant of an output with spending method $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ and that lower bound of value holds for the duration of the funding procedure, i.e. we have proven the first claim of the first bullet.

We will now prove that the newly funded party R can close its channel securely. After R receives (FUNDED, host_P, \dots) by P and before moving to the OPEN state, it receives $\text{sig}_{\bar{R},C,0} = \text{sig}(C_{R,0}, pk_{\bar{R},F})$ and sends $\text{sig}_{R,C,0} = \text{sig}(C_{R,0}, pk_{R,F})$. Both these transactions spend o_R . As we showed before, if R receives (FORCECLOSE) by \mathcal{E} then o_R eventually ends up on-chain. After receiving (CLOSED) from host_P , R attempts to add $C_{R,0}$ to $\mathcal{G}_{\text{Ledger}}$, which may only fail if $C_{\bar{R},0}$ ends up on-chain instead. Similar to the case of P , both these transactions have an $(f, pk_{R,\text{out}})$ output. This output of $C_{R,0}$ is timelocked, but the alternative spending method cannot be used as R never signed a transaction that uses it (as it is reserved for revocation, which has not taken place yet) so the timelock will expire and the desired spending method will be available. We have now proven that if R 's channel is funded to completion (i.e. R moves to the OPEN state for the first time) then it can close its channel for a $(f, pk_{R,\text{out}})$ output that is a descendant of o_R . We have therefore proven the first bullet.

We now move on to the second bullet. In case P is the **fundee** (i.e. $i = n$), then the same arguments as in the previous bullet hold here with “WAITING FOR INBOUND REVOCATION” replaced with “WAITING FOR OUTBOUND REVOCATION”, $o_{1,2}$ with $o_{n-1,n}$, $\text{TX}_{1,1}$ with $\text{TX}_{n,1}$, $B_{1,1}$ with $B_{n,1}$, $\text{TX}_{2,1}$ with $\text{TX}_{n-1,1}$, $B_{2,1}$ with $B_{n-1,1}$, $(\text{TX}_{2,2,k})_{k>2}$ with $(\text{TX}_{n-1,2,k})_{k<n-1}$, $(B_{2,2,k})_{k>2}$ with $(B_{n-1,2,k})_{k<n-1}$, $(\text{TX}_{2,3,1,k})_{k>2}$ with $(\text{TX}_{n-1,3,n,k})_{k<n-1}$, $(B_{2,3,1,k})_{k>2}$ with $(B_{n-1,3,n,k})_{k<n-1}$, t_2 with t_{n-1} , $\text{TX}_{i,3,2,k}$ with $\text{TX}_{i,3,n-1,k}$, $B_{i,3,2,k}$ with $B_{i,3,n-1,k}$, i is initialized to $n - 2$ in l. 2 of Fig. 65, i is decremented instead of incremented in l. 12 of the same Figure and f is replaced with 0. This is so because these two cases are symmetric.

In case P is not the **fundee** ($1 < i < n$), then we only need to prove the first statement of the second bullet. By the induction hypothesis and since **sibling** is kindred, we know that both P 's and **sibling**'s funding outputs either are or can be eventually put on-chain and that P 's funding output has at least $c_P = \sum_{s \in C} \sum_{x \in s} x$ coins. If P is on the “left” of its **sibling** (i.e. there is an untrusted party that sent the (VIRTUALISING, ...) message to P which triggered the latter to move to the VIRTUALISING state and to send a (VIRTUALISING, ...) message to its own **sibling**), the “left” funding output o_{left} (the one held with the untrusted party to the left) can be spent by one of $\text{TX}_{i,1}$, $(\text{TX}_{i,2,k})_{k>i}$, $\text{TX}_{i-1,1}$,

or $(\text{TX}_{i-1,2,k})_{k < i-1}$, as these are the only transactions that P has signed with $sk_{P,F}$. All these transactions have a $(c_P + c_{\bar{P}} - f, 2/\{pk_{P,F'}, pk_{\bar{P},F'}\})$ output that can in turn be spent by either $C_{P,0}$ or $C_{\bar{P},0}$, both of which have an output of value c_P and a $pk_{P,\text{out}}$ spending method and no other spending method can be used (as P has not signed the “revocation” spending method of $C_{P,0}$).

In the case that P is to the right of its **sibling** (i.e. P receives by **sibling** the (VIRTUALISING, ...) message that causes P 's transition to the VIRTUALISING state), the “right” funding output o_{right} (the one held with the untrusted party to the right) can be spent by one of $\text{TX}_{i,1}$, $(\text{TX}_{i,2,k})_{k < i}$, $\text{TX}_{i+1,1}$, or $(\text{TX}_{i+1,2,k})_{k > i+1}$, as these are the only transactions that P has signed with $sk_{P,F}$. All these transactions have a $(c_P + c_{\bar{P}} - f, 2/\{pk_{P,F'}, pk_{\bar{P},F'}\})$ output that can in turn be spent by either $C_{P,0}$ or $C_{\bar{P},0}$, both of which have an output of value $c_P - f$ and a $pk_{P,\text{out}}$ spending method and no other spending method can be used (as P has not signed the “revocation” spending method of $C_{P,0}$). P can get the remaining f coins as follows: $\text{TX}_{i,1}$ and all of $(\text{TX}_{i,2,k})_{k < i}$ already have an $(f, pk_{P,\text{out}})$ output (Note that this output is also encumbered with a timelock, but the alternative spending method cannot be used as host_P has not signed the required revocation transaction). If instead $\text{TX}_{i+1,1}$ or one of $(\text{TX}_{i+1,2,k_2})_{k_2 > i+1}$ spends o_{right} , then P will publish $\text{TX}_{i,2,i+1}$ or $\text{TX}_{i,2,k_2}$ respectively if o_{left} is unspent, otherwise o_{left} is spent by one of $\text{TX}_{i-1,1}$ or $(\text{TX}_{i-1,2,k_1})_{k_1 < i-1}$ in which case P will publish one of $\text{TX}_{i,3,k_1,i+1}$, $\text{TX}_{i,3,i-1,k_2}$, $\text{TX}_{i,3,i-1,i+1}$ or $\text{TX}_{i,3,k_1,k_2}$. In particular, $\text{TX}_{i,3,k_1,i+1}$ is published if $\text{TX}_{i-1,2,k_1}$ and $\text{TX}_{i+1,1}$ are on-chain, $\text{TX}_{i,3,i-1,k_2}$ is published if $\text{TX}_{i-1,1}$ and $\text{TX}_{i+1,2,k_2}$ are on-chain, $\text{TX}_{i,3,i-1,i+1}$ is published if $\text{TX}_{i-1,1}$ and $\text{TX}_{i+1,1}$ are on-chain, or $\text{TX}_{i,3,k_1,k_2}$ is published if $\text{TX}_{i-1,2,k_1}$ and $\text{TX}_{i+1,2,k_2}$ are on-chain. All these transactions include an $(f, pk_{P,\text{out}})$ output for which the revocation-based spending method cannot be used since host_P has not produced the corresponding signature for the revocation transaction. We have therefore covered all cases and proven the second bullet.

We now focus on the third bullet. Once more the induction hypothesis guarantees that before (CHECK COOP CLOSE, ...) was received, P could close the channel resulting in on-chain outputs exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output o_F with a $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ spending method that have a sum value of $c_P = \sum_{s \in C} \sum_{x \in s} x$. When P receives (CHECK COOP

CLOSE, ...), it moves to the COOP CLOSING state before returning to the OPEN state. It verifies the counterparty's signature on the new commitment transaction $C_{P,i+1}$, (Fig. 63, l. 16) which spends the latest old funding output (Fig. 63, l. 14), effectively removing one virtualisation layer. In $C_{P,i+1}$ P owns c'_2 more coins than before that moment (Fig. 63, l. 15). It then signs the corresponding commitment transaction for the counterparty (Fig. 63, l. 91) and expects a valid signature for the revocation transaction of the old commitment transaction of the counterparty (Fig. 63, l. 126). Once these are received, P transitions to the OPEN state. If the o_F output is spent while P is in the COOP CLOSING state, it can be spent by one of $C_{P,i+1}$ or some of $(C_{\bar{P},j})_{0 \leq j \leq i+1}$. If it is spent by $C_{P,i+1}$ or $C_{\bar{P},i+1}$, then these two transactions have a $(c_P + c'_2, pk_{P,\text{out}})$ output. (Note that the former is encumbered with a timelock, but the alternative spending

method cannot be used as P has not signed $R_{\bar{P},i+1}$.) If it is spent by $C_{\bar{P},i}$ then a $(c_P, pk_{P,\text{out}})$ output becomes available instead, therefore P can still get the c_P coins that correspond to the previous state. If any of $(C_{\bar{P},j})_{0 \leq j < i}$ spends this or another of our past funding outputs then it makes available a $pk_{P,\text{out}}$ output with the coins that P had at state j and additionally P can publish $R_{P,j}$ that spends \bar{P} 's output of $C_{\bar{P},j}$ and obtain the entirety of \bar{P} 's coins at state j for a total of $c_P + c_{\bar{P}}$ coins. What is more, if o_F is spent by any virtual transaction, then host_P will punish the publisher of such transaction with the corresponding virtual revocation transaction (Fig. 63, l. 35, l. 38, l. 62, l. 110, l. 111 and l. 114) at the latest when P receives (CHECK CHAIN FOR CLOSED) (Fig. 40, l. 17) – note that the latter message is received periodically by P , since it is a non-negligent party. The virtual revocation transaction gives a sum equal to the entirety of the channel's funds to P . Therefore in every case P can claim at least c_P coins. In the case that P instead subsequently receives a valid signature to $R_{P,i}$ (Fig. 63, l. 126) and moves to the OPEN state, the above analysis of what can happen when o_F is spent holds similarly, with the difference that if \bar{P} spends o_F with $C_{\bar{P},i}$ now P can publish $R_{P,i}$ which gives P the coins of \bar{P} . Therefore with this difference P is now guaranteed to gain at least $c_P + c'_2$ coins upon channel closure. We have therefore proven the third bullet.

We now focus on the fourth bullet. Once more the induction hypothesis guarantees that before (COOP CLOSE SIGN COMM, ...) was received, P could close the channel resulting in on-chain outputs exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output o_F with a $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ spending method that have a sum value of $c_P = \sum_{s \in C} \sum_{x \in s} x$. When P receives (COOP CLOSE SIGN COMM, ...), it moves to the COOP CLOSING state before returning to the OPEN state. It signs the new commitment transaction for the counterparty (Fig. 63, l. 27) which spends the latest old funding output (Fig. 63, l. 25), effectively removing one virtualisation layer. In $C_{P,i+1}$ P owns $c_{\text{virt}} - c'_1$ less coins than before that moment (Fig. 63, l. 26) – note that P now lost access to c_{virt} coins from the refund output of its virtual transactions. It then verifies the counterparty's signatures on the corresponding new local commitment transaction $C_{P,i+1}$, (Fig. 63, l. 46) and on the revocation transaction of the old commitment transaction of the counterparty (Fig. 63, l. 49). Once these are received, P transitions to the OPEN state. If the o_F output is spent while P is in the COOP CLOSING state, it can be spent by one of $C_{P,i+1}$ or some of $(C_{\bar{P},j})_{0 \leq j \leq i+1}$. If it is spent by $C_{P,i+1}$ or $C_{\bar{P},i+1}$, then these two transactions have a $(c_P + c'_1, pk_{P,\text{out}})$ output. (Note that the former is encumbered with a timelock, but the alternative spending method cannot be used as P has not signed $R_{\bar{P},i+1}$.) If it is spent by $C_{\bar{P},i}$ then a $(c_P, pk_{P,\text{out}})$ output becomes available instead, therefore P can still get the c_P coins that correspond to the previous state. If any of $(C_{\bar{P},j})_{0 \leq j < i}$ spends this or another of our past funding outputs then it makes available a $pk_{P,\text{out}}$ output with the coins that P had at state j and additionally P can publish $R_{P,j}$ that spends \bar{P} 's output of $C_{\bar{P},j}$ and obtain the entirety of \bar{P} 's coins at state j for a total of $c_P + c_{\bar{P}}$ coins. Similarly to the previous bullet, if o_F is spent by any virtual transaction, then host_P will punish the publisher

and P will obtain a sum equal to the entirety of the channel's funds. Therefore in every case P can claim at least c_P coins. In the case that P instead subsequently receives a valid signature to $R_{P,i}$ (Fig. 63, l. 126) and moves to the OPEN state, the above analysis of what can happen when o_F holds similarly, with the difference that if \bar{P} spends o_F with $C_{\bar{P},i}$ now P can publish $R_{P,i}$ which gives P the coins of \bar{P} . Therefore with this difference P is now guaranteed to gain at least $c_P - c_{\text{virt}} + c'_1$ coins upon channel closure. This proves the first claim of the fourth bullet.

Regarding the second claim, we observe that P can only move to the OPEN state if previously a local kindred LN ITI R moves to the OPEN state as well. Via direct application of the previous claim of the currently analysed bullet, R has gained c'_2 coins in the process, therefore guaranteeing that P and R have on aggregate access to the same number of coins as before the cooperative closing. What is more, throughout the cooperative closing process both parties had access to at least c_P and c_R coins respectively, thus ensuring that no loss of coins is possible. We have now proven the fourth bullet.

Moving on to the fifth bullet, the same reasoning as that of the treatment of the previous bullet holds, albeit with the **guest**'s signature verifications as they appear in Fig. 47.

The first claim of the sixth bullet holds due to an argument identical to that provided for the third bullet, since in both cases the relevant parts of the protocol execution are the same. Note that **funder**'s signature for the revocation of the lastt commitment transaction of the virtual channel has not been yet verified, but this is of no consequence for our balance as all other revocation signatures have been already verified and the connection with the **funder** has been severed due to the successful cooperative closing.

Regarding now the seventh bullet, once again the induction hypothesis guarantees that before (PAY, d) was received, P could close the channel resulting in on-chain outputs exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output with a $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ spending method that have a sum value of $c_P = \sum_{s \in C} \sum_{x \in s} x$. (Note that $\sum_{s \in C'} \sum_{x \in s} x = d + \sum_{s \in C} \sum_{x \in s} x$.) When P receives (PAY, d) while in the OPEN state, it moves to the WAITING FOR COMMITMENT SIGNED state before returning to the OPEN state. It signs (Fig. 35, l. 2) the new commitment transaction $C_{\bar{P},i+1}$ in which the counterparty owns d more coins than before that moment (Fig. 35, l. 1), sends the signature to the counterparty (Fig. 35, l. 5) and expects valid signatures on its own updated commitment transaction (Fig. 36, l. 1) and the revocation transaction for the old commitment transaction of the counterparty (Fig. 36, l. 3). Upon verifying them, P transitions to the OPEN state. Note that if the counterparty does not respond or if it responds with missing/invalid signatures, either P can close the channel with the old commitment transaction $C_{P,i}$ exactly like before the update started (as it has not yet sent the signature for the old revocation transaction), or the counterparty will close the channel either with the new or with the old commitment transaction. In all cases in which validation fails and the channel closes, there is an output with a $pk_{P,\text{out}}$ spending method and no other useable

spending method that carries at least $c_P - d$ coins. Only if the verification succeeds does P sign (Fig. 36, l. 5) and send (Fig. 36, l. 17) the counterparty's revocation transaction for P 's previous commitment transaction.

Similarly to previous bullets, if $\text{host}_P \neq \text{"ledger"}$ the funding output can be put on-chain, otherwise the funding output is already on-chain. In both cases, since the closing procedure continues, one of $C_{P,i+1}$, $(C_{\bar{P},j})_{0 \leq j \leq i+1}$ will end up on-chain. If $C_{\bar{P},j}$ for some $j < i+1$ is on-chain, then P submits $R_{P,j}$ (we discussed how P obtained $R_{P,i}$ and the rest of the cases are covered by induction) and takes the entire value of the channel which is at least $c_P - d$. If $C_{\bar{P},i+1}$ is on-chain, it has a $(c_P - d, pk_{P,\text{out}})$ output. If $C_{P,i+1}$ is on-chain, it has an output of value $c_P - d$, a timelocked $pk_{P,\text{out}}$ spending method and a non-timelocked spending method that needs the signature made with $sk_{P,R}$ on $R_{\bar{P},i+1}$. P however has not generated that signature, therefore this spending method cannot be used and the timelock will expire, therefore in all cases outputs that descend from the funding output, can be spent exclusively by $pk_{P,\text{out}}$ and carry at least $c_P - d$ coins are put on-chain. We have proven the seventh bullet.

For the eighth and last bullet, again by the induction hypothesis, before (GET PAID, e) was received P could close the channel resulting in on-chain outputs exclusively spendable or already spent by $pk_{P,\text{out}}$ that are descendants of an output o_F with a $2/\{pk_{P,F}, pk_{\bar{P},F}\}$ spending method and have a sum value of $c_P = \sum_{s \in C} \sum_{x \in s} x$. (Note that $e + \sum_{s \in C'} \sum_{x \in s} x = \sum_{s \in C} \sum_{x \in s} x$ and that o_F either is already on-chain or can be eventually put on-chain as we have argued in the previous bullets by the induction hypothesis.) When P receives (GET PAID, e) while in the OPEN state, if the balance of the counterparty is enough it moves to the WAITING TO GET PAID state (Fig. 38, l. 6). If subsequently it receives a valid signature for $C_{P,i+1}$ (Fig. 35, l. 9) which is a commitment transaction that can spend the o_F output and gives to P an additional e coins compared to $C_{P,i}$. Subsequently P 's state transitions to WAITING FOR PAY REVOCATION and sends signatures for $C_{\bar{P},i+1}$ and $R_{\bar{P},i}$ to \bar{P} . If the o_F output is spent while P is in the latter state, it can be spent by one of $C_{P,i+1}$ or $(C_{\bar{P},j})_{0 \leq j \leq i+1}$. If it is spent by $C_{P,i+1}$ or $C_{\bar{P},i+1}$, then these two transactions have a $(c_P + e, pk_{P,\text{out}})$ output. (Note that the former is encumbered with a timelock, but the alternative spending method cannot be used as P has not signed $R_{\bar{P},i+1}$.) If it is spent by $C_{\bar{P},i}$ then a $(c_P, pk_{P,\text{out}})$ output becomes available instead, therefore P can still get the c_P coins that correspond to the previous state. If any of $(C_{\bar{P},j})_{0 \leq j < i}$ spends o_F then it makes available a $pk_{P,\text{out}}$ output with the coins that \bar{P} had at state j and additionally P can publish $R_{P,j}$ that spends \bar{P} 's output of $C_{\bar{P},j}$ and obtain the entirety of \bar{P} 's coins at state j for a total of $c_P + c_{\bar{P}}$ coins. Therefore in every case P can claim at least c_P coins. In the case that P instead subsequently receives a valid signature to $R_{P,i}$ (Fig. 36, l. 20) it finally moves to the OPEN state once again. In this state the above analysis of what can happen when o_F holds similarly, with the difference that if \bar{P} spends o_F with $C_{\bar{P},i}$ now P can publish $R_{P,i}$ which gives P the coins of \bar{P} . Therefore with this difference P is now guaranteed to gain at least $c_P + e$ coins upon channel closure. We have therefore proven the eighth bullet and with it the first bullet of the Lemma.

We now turn to proving the second bullet of the Lemma. We will take advantage of the results that have been derived earlier in this proof. If P is the **funder** of the virtual channel in process of cooperatively closing, it ensures that $c'_1 = c_P \wedge c'_2 = c_{\bar{P}}$ (Fig. 47, l. 4). If P is the **fundee**, it requests that the virtual channel be closed with the current honest coin balance (Fig. 46, l. 6), in which case it is $c'_1 = c_{\bar{P}} \wedge c'_2 = c_P$. Due to the arguments proving the first Lemma bullet, we know that

$$c_P = \sum_{s \in C} \sum_{x \in s} x \geq \phi \cdot c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^j r_i + \sum_{i=1}^k l_i . \quad (5)$$

Just before the splitting of the two alternative scenarios, party S is entitled to c_b coins, since (i) in the first scenario all other parties honestly follow the protocol and thus they do not lose any coins to S and (ii) no action during the first scenario causes any transfer of coins. As we saw previously, if P transitions to the COOP CLOSED state, then S has also transitioned from the COOP CLOSING to the OPEN state and benefitted from an increase of the coins it can exclusively spend by c_P . It therefore holds that the difference of the coins $c_t - c_b$ that P owns at the end of the two scenarios is exactly c_P and due to (5) we can directly derive the required (4). The Lemma has now been proven.

Lemma 5 (Ideal world balance). *Consider an ideal world execution with functionality $\mathcal{G}_{\text{Chan}}$ and simulator \mathcal{S} . Let $P \in \{\text{Alice}, \text{Bob}\}$ one of the two parties of $\mathcal{G}_{\text{Chan}}$. Assume that all of the following are true:*

- $\text{State}_P \neq \text{IGNORED}$,
- P has transitioned to the OPEN State at least once. Additionally, if $P = \text{Alice}$, it has received (OPEN, c, \dots) by \mathcal{E} prior to transitioning to the OPEN State,
- P [has received $(\text{FUND ME}, f_i, \dots)$ as input by another $\mathcal{G}_{\text{Chan}}/\text{LN ITI}$ while State_P was OPEN and P subsequently transitioned to OPEN State] n times,
- $\mathcal{G}_{\text{Ledger}}$ [has received $(\text{COOP CLOSING}, P, r_i)$ by \mathcal{S} while State_P was OPEN and subsequently P transitioned to OPEN State] k times,
- P [has received (PAY, d_i) by \mathcal{E} while State_P was OPEN and P subsequently transitioned to OPEN State] m times,
- P [has received $(\text{GET PAID}, e_i)$ by \mathcal{E} while State_P was OPEN and P subsequently transitioned to OPEN State] l times.

Let $\phi = 1$ if $P = \text{Alice}$, or $\phi = 0$ if $P = \text{Bob}$. If $\mathcal{G}_{\text{Chan}}$ receives $(\text{FORCECLOSE}, P)$ by \mathcal{S} , then the following holds with overwhelming probability on the security parameter:

$$\text{balance}_P = \phi \cdot c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^k r_i \quad (6)$$

Proof (Proof of Lemma 5). We will prove the Lemma by following the evolution of the balance_P variable.

- When $\mathcal{G}_{\text{Chan}}$ is activated for the first time, it sets $\text{balance}_P \leftarrow 0$ (Fig. 9, l. 1).
- If $P = \text{Alice}$ and it receives (OPEN, c, \dots) by \mathcal{E} , it stores c (Fig. 9, l. 11). If later State_P becomes OPEN, $\mathcal{G}_{\text{Chan}}$ sets $\text{balance}_P \leftarrow c$ (Fig. 9, ll. 14 or 34). In contrast, if $P = \text{Bob}$, it is $\text{balance}_P = 0$ until at least the first transition of State_P to OPEN (Fig. 9).
- Every time that P receives input $(\text{FUND ME}, f_i, \dots)$ by another party while $\text{State}_P = \text{OPEN}$, P stores f_i (Fig. 11, l. 1). The next time State_P transitions to OPEN (if such a transition happens), balance_P is decremented by f_i (Fig. 11, l. 27). Therefore, if this cycle happens $n \geq 0$ times, balance_P will be decremented by $\sum_{i=1}^n f_i$ in total.
- Every time $\mathcal{G}_{\text{Ledger}}$ receives $(\text{COOP CLOSING}, P, r_i)$ by \mathcal{S} while State_P is OPEN, r_i is stored (Fig. 13, l. 1). The next time State_P transitions to OPEN (if such a transition happens), balance_P is incremented by r_i (Fig. 13, l. 9). Therefore, if this cycle happens $k \geq 0$ times, balance_P will be incremented by $\sum_{i=1}^k r_i$ in total.
- Every time P receives input (PAY, d_i) by \mathcal{E} while $\text{State}_P = \text{OPEN}$, d_i is stored (Fig. 10, l. 2). The next time State_P transitions to OPEN (if such a transition happens), balance_P is decremented by d_i (Fig. 10, l. 13). Therefore, if this cycle happens $m \geq 0$ times, balance_P will be decremented by $\sum_{i=1}^m d_i$ in total.
- Every time P receives input $(\text{GET PAID}, e_i)$ by \mathcal{E} while $\text{State}_P = \text{OPEN}$, e_i is stored (Fig. 10, l. 7). The next time State_P transitions to OPEN (if such a transition happens) balance_P is incremented by e_i (Fig. 10, l. 19). Therefore, if this cycle happens $l \geq 0$ times, balance_P will be incremented by $\sum_{i=1}^l e_i$ in total.

On aggregate, after the above are completed and then $\mathcal{G}_{\text{Chan}}$ receives $(\text{FORCECLOSE}, P)$ by \mathcal{S} , it is $\text{balance}_P = c - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^k r_i$ if $P = \text{Alice}$, or else if $P = \text{Bob}$, $\text{balance}_P = - \sum_{i=1}^n f_i - \sum_{i=1}^m d_i + \sum_{i=1}^l e_i + \sum_{i=1}^k r_i$.

Proof (Proof of Lemma 3). We prove the Lemma in two steps. We first show that if the conditions of Lemma 5 hold, then the conditions of Lemma 4 for the real world execution with protocol LN and the same \mathcal{E} and \mathcal{A} hold as well for the same k, m, n and l values.

For State_P to become IGNORED, either \mathcal{S} has to send $(\text{BECAME CORRUPTED OR NEGLIGENT}, P)$ or host_P must output $(\text{ENABLER USED REVOCATION})$ to $\mathcal{G}_{\text{Chan}}$ (Fig. 9, l. 5). The first case only happens when either P receives (CORRUPT) by \mathcal{A} (Fig. 23, l. 1), which means that the simulated P is not honest anymore, or when P becomes **negligent** (Fig. 23, l. 4), which means that the first condition of Lemma 4 is violated. In the second case, it is $\text{host}_P \neq \mathcal{G}_{\text{Ledger}}$ and the

state of host_P is GUEST PUNISHED (Fig. 64, ll. 1 or 12), so in case P receives (FORCECLOSE) by \mathcal{E} the output of host_P will be (GUEST PUNISHED) (Fig. 61, l. 4). In all cases, some condition of Lemma 4 is violated.

For State_P to become OPEN at least once, the following sequence of events must take place (Fig. 9): If $P = \text{Alice}$, it must receive (INIT, pk) by \mathcal{E} when $\text{State}_P = \text{UNINIT}$, then either receive (OPEN, c , $\mathcal{G}_{\text{Ledger}}$, ...) by \mathcal{E} and (BASE OPEN) by \mathcal{S} or (OPEN, c , **hops** ($\neq \mathcal{G}_{\text{Ledger}}$), ...) by \mathcal{E} , (FUNDED, HOST, ...) by **hops**[0].left and (VIRTUAL OPEN) by \mathcal{S} . In either case, \mathcal{S} only sends its message only if all its simulated honest parties move to the OPEN state (Fig. 23, l. 10), therefore if the second condition of Lemma 5 holds and $P = \text{Alice}$, then the second condition of Lemma 4 holds as well. The same line of reasoning can be used to deduce that if $P = \text{Bob}$, then State_P will become OPEN for the first time only if all honest simulated parties move to the OPEN state, therefore once more the second condition of Lemma 5 holds only if the second condition of Lemma 4 holds as well. We also observe that, if both parties are honest, they will transition to the OPEN state simultaneously.

Regarding the third Lemma 5 condition, we assume (and will later show) that if both parties are honest and the state of one is OPEN, then the state of the other is also OPEN. Each time P receives input (FUND ME, f , ...) by $R \in \{\mathcal{G}_{\text{Chan}}, \text{LN}\}$, State_P transitions to PENDING FUND, subsequently when a command to define a new VIRT ITI through P is intercepted by $\mathcal{G}_{\text{Chan}}$, State_P transitions to TENTATIVE FUND and afterwards when \mathcal{S} sends (FUND) to $\mathcal{G}_{\text{Chan}}$, State_P transitions to SYNC FUND. In parallel, if $\text{State}_{\bar{P}} = \text{IGNORED}$, then State_P transitions directly back to OPEN. If on the other hand $\text{State}_{\bar{P}} = \text{OPEN}$ and $\mathcal{G}_{\text{Chan}}$ intercepts a similar VIRT ITI definition command through \bar{P} , $\text{State}_{\bar{P}}$ transitions to TENTATIVE HELP FUND. On receiving the aforementioned (FUND) message by \mathcal{S} and given that $\text{State}_{\bar{P}} = \text{TENTATIVE HELP FUND}$, $\mathcal{G}_{\text{Chan}}$ also sets $\text{State}_{\bar{P}}$ to SYNC HELP FUND. Then both $\text{State}_{\bar{P}}$ and State_P transition simultaneously to OPEN (Fig. 11). This sequence of events may repeat any $n \geq 0$ times. We observe that throughout these steps, honest simulated P has received (FUND ME, f , ...) and that \mathcal{S} only sends (FUND) when all honest simulated parties have transitioned to the OPEN state (Fig. 23, l. 18 and Fig. 33, l. 12), so the third condition of Lemma 4 holds with the same n as that of Lemma 5.

Moving on to the fourth Lemma 5 condition, we again assume that if both parties are honest and the state of one is OPEN, then the state of the other is also OPEN. Each time $\mathcal{G}_{\text{Chan}}$ receives (COOP CLOSING, P , r) by \mathcal{S} , State_P transitions to COOP CLOSING and subsequently when \mathcal{S} sends (COOP CLOSED, P) to $\mathcal{G}_{\text{Chan}}$, if $\text{layer}_P = 0$ then State_P transitions to COOP CLOSED, else State_P transitions to OPEN. This sequence of events may repeat any $k \geq 0$ times. We observe that throughout these steps, honest simulated P has transitioned to the COOP CLOSING state and that \mathcal{S} only sends (COOP CLOSED, P) when honest simulated P transitions to either OPEN or COOP CLOSED state, so the sum of j (from the fourth condition of Lemma 4) plus k (from the fifth condition of Lemma 4) is equal to the k of Lemma 5.

Regarding the sixth Lemma 5 condition, we again assume that if both parties are honest and the state of one is OPEN, then the state of the other is also OPEN. Each time P receives input (PAY, d) by \mathcal{E} , $State_P$ transitions to TENTATIVE PAY and subsequently when \mathcal{S} sends (PAY) to $\mathcal{G}_{\text{Chan}}$, $State_P$ transitions to (SYNC PAY, d). In parallel, if $State_{\bar{P}} = \text{IGNORED}$, then $State_P$ transitions directly back to OPEN. If on the other hand $State_{\bar{P}} = \text{OPEN}$ and $\mathcal{G}_{\text{Chan}}$ receives (GET PAID, d) by \mathcal{E} addressed to \bar{P} , $State_{\bar{P}}$ transitions to TENTATIVE GET PAID. On receiving the aforementioned (PAY) message by \mathcal{S} and given that $State_{\bar{P}} = \text{TENTATIVE GET PAID}$, $\mathcal{G}_{\text{Chan}}$ also sets $State_{\bar{P}}$ to SYNC GET PAID. Then both $State_P$ and $State_{\bar{P}}$ transition simultaneously to OPEN (Fig. 10). This sequence of events may repeat any $m \geq 0$ times. We observe that throughout these steps, honest simulated P has received (PAY, d) and that \mathcal{S} only sends (PAY) when all honest simulated parties have completed sending or receiving the payment (Fig. 23, l. 16), so the sixth condition of Lemma 4 holds with the same m as that of Lemma 5. As far as the seventh condition of Lemma 5 goes, we observe that this case is symmetric to the one discussed for its sixth condition above if we swap P and \bar{P} , therefore we deduce that if Lemma 5 holds with some l , then Lemma 4 holds with the same l .

As promised, we here argue that if both parties are honest and one party moves to the OPEN state, then the other party will move to the OPEN state as well. We already saw that the first time one party moves to the OPEN state, it will happen simultaneously with the same transition for the other party. We also saw that, when a party transitions from the SYNC HELP FUND or the SYNC FUND state to the OPEN state, then the other party will also transition to the OPEN state simultaneously. Additionally, we saw that if one party transitions from the COOP CLOSING state to the OPEN state, the other party will also transition to the OPEN state simultaneously. Furthermore, we saw that if one party transitions from the SYNC PAY or the SYNC GET PAID state to the OPEN state, the other party will also transition to the OPEN state simultaneously. Lastly we notice that we have exhausted all manners in which a party can transition to the OPEN state, therefore we have proven that transitions of honest parties to the OPEN state happen simultaneously.

Now, given that \mathcal{S} internally simulates faithfully both LN parties and that $\mathcal{G}_{\text{Chan}}$ relinquishes to \mathcal{S} complete control of the external communication of the parties as long as it does not halt, we deduce that \mathcal{S} replicates the behaviour of the aforementioned real world. By combining these facts with the consequences of the two Lemmas and the check that leads $\mathcal{G}_{\text{Chan}}$ to halt if it fails (Fig. 12, l. 18), we deduce that if the conditions of Lemma 5 hold for the honest parties of $\mathcal{G}_{\text{Chan}}$ and their kindred parties, then the functionality halts only with negligible probability.

In the second proof step, we show that if the conditions of Lemma 5 do not hold, then the check of Fig. 12, l. 18 never takes place. We first discuss the $State_P = \text{IGNORED}$ case. We observe that the IGNORED $State$ is a sink state, as there is no way to leave it once in. Additionally, for the balance check to happen, $\mathcal{G}_{\text{Chan}}$ must receive (CLOSED, P) by \mathcal{S} when $State_P \neq \text{IGNORED}$ (Fig. 12, l. 9).

We deduce that, once $State_P = \text{IGNORED}$, the balance check will not happen. Moving to the case where $State_P$ has never been OPEN, we observe that it is impossible to move to any of the states required by l. 9 of Fig. 12 without first having been in the OPEN state. Moreover if $P = \text{Alice}$, it is impossible to reach the OPEN state without receiving input (OPEN, c, \dots) by \mathcal{E} . Lastly, as we have observed already, the three last conditions of Lemma 5 are always satisfied. We conclude that if the conditions to Lemma 5 do not hold, then the check of Fig. 12, l. 18 does not happen and therefore $\mathcal{G}_{\text{Chan}}$ does not halt.

On aggregate, $\mathcal{G}_{\text{Chan}}$ may only halt with negligible probability in the security parameter.

Acknowledgements: Research partly supported by PRIVILEGE: EU Project No. 780477 and the Blockchain Technology Laboratory – University of Edinburgh.

References

1. Raiden network, <https://raiden.network/>
2. Adler, J.: The why’s of optimistic rollup. <https://medium.com/@adlerjohn/the-why-s-of-optimistic-rollup-7c6a22cbb61a> (November 2019)
3. Armknecht, F., Karame, G.O., Mandal, A., Youssef, F., Zenner, E.: Ripple: Overview and outlook. In: Trust and Trustworthy Computing - 8th International Conference, TRUST 2015, Heraklion, Greece, August 24-26, 2015, Proceedings. pp. 163–180 (2015). https://doi.org/10.1007/978-3-319-22846-4_10, https://doi.org/10.1007/978-3-319-22846-4_10
4. Aumayr, L., Ersoy, O., Erwig, A., Faust, S., Hostáková, K., Maffei, M., Moreno-Sanchez, P., Riahi, S.: Generalized bitcoin-compatible channels. IACR Cryptol. ePrint Arch. p. 476 (2020), <https://eprint.iacr.org/2020/476>
5. Aumayr, L., Maffei, M., Ersoy, O., Erwig, A., Faust, S., Riahi, S., Hostáková, K., Moreno-Sanchez, P.: Bitcoin-compatible virtual channels. In: 2021 IEEE Symposium on Security and Privacy (SP). pp. 901–918 (2021). <https://doi.org/10.1109/SP40001.2021.00097>
6. Aumayr, L., Moreno-Sanchez, P., Kate, A., Maffei, M.: Donner: Utxo-based virtual channels across multiple hops. Cryptology ePrint Archive, Report 2021/855 (2021), <https://eprint.iacr.org/2021/855>
7. Avarikioti, G., Kogias, E.K., Wattenhofer, R., Zindros, D.: Brick: Asynchronous payment channels (2020)
8. Back, A., Corallo, M., Dashjr, L., Friedenbach, M., Maxwell, G., Miller, A., Poelstra, A., Timón, J., Wuille, P.: Enabling blockchain innovations with pegged sidechains (2014), <http://web.archive.org/save/https://pdfs.semanticscholar.org/1b23/cd2050d5000c05e1da3c9997b308ad5b7903.pdf>
9. Badertscher, C., Canetti, R., Hesse, J., Tackmann, B., Zikas, V.: Universal composition with global subroutines: Capturing global setup within plain UC. In: Theory of Cryptography - 18th International Conference, TCC 2020, Durham, NC, USA, November 16-19, 2020, Proceedings, Part III. pp. 1–30 (2020). https://doi.org/10.1007/978-3-030-64381-2_1, https://doi.org/10.1007/978-3-030-64381-2_1

10. Badertscher, C., Gaži, P., Kiayias, A., Russell, A., Zikas, V.: Ouroboros genesis: Composable proof-of-stake blockchains with dynamic availability. In: Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security. pp. 913–930. ACM (2018)
11. Badertscher, C., Maurer, U., Tschudi, D., Zikas, V.: Bitcoin as a transaction ledger: A composable treatment. In: Annual International Cryptology Conference. pp. 324–356. Springer (2017)
12. Burchert, C., Decker, C., Wattenhofer, R.: Scalable funding of bitcoin micropayment channel networks. In: The Royal Society (2018). <https://doi.org/10.1098/rsos.180089>
13. Canetti, R.: Universally composable security: A new paradigm for cryptographic protocols. In: 42nd Annual Symposium on Foundations of Computer Science, FOCS 2001, 14-17 October 2001, Las Vegas, Nevada, USA. pp. 136–145 (2001). <https://doi.org/10.1109/SFCS.2001.959888>, <https://eprint.iacr.org/2000/067.pdf>
14. Chakravarty, M.M.T., Coretti, S., Fitzi, M., Gazi, P., Kant, P., Kiayias, A., Russell, A.: Hydra: Fast isomorphic state channels. Cryptology ePrint Archive, Report 2020/299 (2020), <https://eprint.iacr.org/2020/299>
15. Chakravarty, M.M.T., Kireev, R., MacKenzie, K., McHale, V., Müller, J., Nemish, A., Nester, C., Peyton Jones, M., Thompson, S., Valentine, R., Wadler, P.: Functional blockchain contracts (2019), <https://iohk.io/en/research/library/papers/functional-blockchain-contracts/>
16. Croman, K., Decker, C., Eyal, I., Gencer, A.E., Juels, A., Kosba, A., Miller, A., Saxena, P., Shi, E., Sirer, E.G., et al.: On scaling decentralized blockchains. In: International Conference on Financial Cryptography and Data Security. pp. 106–125. Springer (2016)
17. Danezis, G., Goldberg, I.: Sphinx: A compact and provably secure mix format. In: Security and Privacy, 2009 30th IEEE Symposium on. pp. 269–282. IEEE (2009)
18. Decker, C., Russell, R., Osuntokun, O.: eltoo: A simple layer2 protocol for bitcoin. <https://blockstream.com/eltoo.pdf>
19. Decker, C., Towns, A.: Sighash_anyprevout for taproot scripts. <https://github.com/bitcoin/bips/blob/master/bip-0118.mediawiki>
20. Decker, C., Wattenhofer, R.: A fast and scalable payment network with bitcoin duplex micropayment channels. In: Symposium on Self-Stabilizing Systems. pp. 3–18. Springer (2015)
21. Dong, M., Liang, Q., Li, X., Liu, J.: Celer network: Bring internet scale to every blockchain (2018)
22. Dziembowski, S., Ekey, L., Faust, S., Hesse, J., Hostáková, K.: Multi-party virtual state channels. In: Ishai, Y., Rijmen, V. (eds.) Advances in Cryptology - EUROCRYPT 2019 - 38th Annual International Conference on the Theory and Applications of Cryptographic Techniques, Darmstadt, Germany, May 19-23, 2019, Proceedings, Part I. Lecture Notes in Computer Science, vol. 11476, pp. 625–656. Springer (2019). https://doi.org/10.1007/978-3-030-17653-2_21, https://doi.org/10.1007/978-3-030-17653-2_21
23. Dziembowski, S., Ekey, L., Faust, S., Malinowski, D.: Perun: Virtual payment hubs over cryptocurrencies. In: 2019 2019 IEEE Symposium on Security and Privacy (SP). pp. 344–361. IEEE Computer Society, Los Alamitos, CA, USA (May 2019). <https://doi.org/10.1109/SP.2019.00020>, <https://doi.ieeecomputersociety.org/10.1109/SP.2019.00020>

24. Dziembowski, S., Fabiański, G., Faust, S., Riahi, S.: Lower bounds for off-chain protocols: Exploring the limits of plasma. Cryptology ePrint Archive, Report 2020/175 (2020), <https://eprint.iacr.org/2020/175>
25. Dziembowski, S., Faust, S., Hostáková, K.: General state channel networks. In: Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, CCS 2018, Toronto, ON, Canada, October 15-19, 2018. pp. 949–966 (2018). <https://doi.org/10.1145/3243734.3243856>, <https://doi.org/10.1145/3243734.3243856>
26. Egger, C., Moreno-Sanchez, P., Maffei, M.: Atomic multi-channel updates with constant collateral in bitcoin-compatible payment-channel networks. In: Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security. pp. 801–815. CCS '19, Association for Computing Machinery, New York, NY, USA (2019). <https://doi.org/10.1145/3319535.3345666>, <https://doi.org/10.1145/3319535.3345666>
27. Gaži, P., Kiayias, A., Zindros, D.: Proof-of-stake sidechains. In: 2019 IEEE Symposium on Security and Privacy (SP). pp. 677–694. IEEE Computer Society, Los Alamitos, CA, USA (may 2019). <https://doi.org/10.1109/SP.2019.00040>, <https://doi.ieeecomputersociety.org/10.1109/SP.2019.00040>
28. Green, M., Miers, I.: Bolt: Anonymous payment channels for decentralized currencies. In: Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security. p. 473–489. CCS '17, Association for Computing Machinery, New York, NY, USA (2017). <https://doi.org/10.1145/3133956.3134093>, <https://doi.org/10.1145/3133956.3134093>
29. Gudgeon, L., Moreno-Sanchez, P., Roos, S., McCorry, P., Gervais, A.: Sok: Layer-two blockchain protocols. In: Financial Cryptography and Data Security - 24th International Conference, FC 2020, Kota Kinabalu, Malaysia, February 10-14, 2020 Revised Selected Papers. pp. 201–226 (2020). https://doi.org/10.1007/978-3-030-51280-4_12, https://doi.org/10.1007/978-3-030-51280-4_12
30. Harris, J., Zohar, A.: Flood & loot: A systemic attack on the lightning network. In: Proceedings of the 2nd ACM Conference on Advances in Financial Technologies. pp. 202–213. AFT '20, Association for Computing Machinery, New York, NY, USA (2020). <https://doi.org/10.1145/3419614.3423248>, <https://doi.org/10.1145/3419614.3423248>
31. Jourenko, M., Larangeira, M., Tanaka, K.: Lightweight virtual payment channels. In: Krenn, S., Shulman, H., Vaudenay, S. (eds.) Cryptology and Network Security. pp. 365–384. Springer International Publishing, Cham (2020)
32. Katz, J., Maurer, U., Tackmann, B., Zikas, V.: Universally composable synchronous computation. In: Theory of Cryptography - 10th Theory of Cryptography Conference, TCC 2013, Tokyo, Japan, March 3-6, 2013. Proceedings. pp. 477–498 (2013). https://doi.org/10.1007/978-3-642-36594-2_27, https://doi.org/10.1007/978-3-642-36594-2_27
33. Khalil, R., Gervais, A.: Revive: Rebalancing off-blockchain payment networks. In: Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security, CCS 2017, Dallas, TX, USA, October 30 - November 03, 2017. pp. 439–453 (2017). <https://doi.org/10.1145/3133956.3134033>, <https://doi.org/10.1145/3133956.3134033>
34. Kiayias, A., Litos, O.S.T.: A composable security treatment of the lightning network. In: 33rd IEEE Computer Security Foundations Symposium, CSF 2020, Boston, MA, USA, June 22-26, 2020. pp. 334–349 (2020).

- <https://doi.org/10.1109/CSF49147.2020.00031>, <https://doi.org/10.1109/CSF49147.2020.00031>
35. Kiayias, A., Zindros, D.: Proof-of-work sidechains. In: Financial Cryptography and Data Security - FC 2019 International Workshops, VOTING and WTSC, St. Kitts, St. Kitts and Nevis, February 18-22, 2019, Revised Selected Papers. pp. 21–34 (2019). https://doi.org/10.1007/978-3-030-43725-1_3, https://doi.org/10.1007/978-3-030-43725-1_3
 36. Konstantopoulos, G.: Plasma cash: Towards more efficient plasma constructions (2019)
 37. Lee, J., Kim, S., Park, S., Moon, S.M.: Routee: A secure payment network routing hub using trusted execution environments (2020)
 38. Liao, J., Zhang, F., Sun, W., Shi, W.: Speedster: A tee-assisted state channel system (2021)
 39. Liao, J., Zhang, F., Sun, W., Shi, W.: Speedster: An efficient multi-party state channel via enclaves. In: Suga, Y., Sakurai, K., Ding, X., Sako, K. (eds.) ASIA CCS '22: ACM Asia Conference on Computer and Communications Security, Nagasaki, Japan, 30 May 2022 - 3 June 2022. pp. 637–651. ACM (2022). <https://doi.org/10.1145/3488932.3523259>, <https://doi.org/10.1145/3488932.3523259>
 40. Lind, J., Eyal, I., Pietzuch, P.R., Sirer, E.G.: Teechan: Payment channels using trusted execution environments. CoRR **abs/1612.07766** (2016), <http://arxiv.org/abs/1612.07766>
 41. Lind, J., Naor, O., Eyal, I., Kelbert, F., Sirer, E.G., Pietzuch, P.: Teechain: A secure payment network with asynchronous blockchain access. In: Proceedings of the 27th ACM Symposium on Operating Systems Principles. pp. 63–79. SOSP '19, Association for Computing Machinery, New York, NY, USA (2019). <https://doi.org/10.1145/3341301.3359627>, <https://doi.org/10.1145/3341301.3359627>
 42. Lindell, Y.: How to simulate it - A tutorial on the simulation proof technique. In: Tutorials on the Foundations of Cryptography, pp. 277–346 (2017). https://doi.org/10.1007/978-3-319-57048-8_6, https://doi.org/10.1007/978-3-319-57048-8_6
 43. Malavolta, G., Moreno-Sanchez, P., Kate, A., Maffei, M.: Silentwhispers: Enforcing security and privacy in decentralized credit networks (2016)
 44. Malavolta, G., Moreno-Sanchez, P., Schneidewind, C., Kate, A., Maffei, M.: Anonymous multi-hop locks for blockchain scalability and interoperability. In: 26th Annual Network and Distributed System Security Symposium, NDSS 2019, San Diego, California, USA, February 24-27, 2019 (2019)
 45. Mazieres, D.: The stellar consensus protocol: A federated model for internet-level consensus. Stellar Development Foundation (2015)
 46. Miller, A., Bentov, I., Kumaresan, R., Cordi, C., McCorry, P.: Sprites and state channels: Payment networks that go faster than lightning (2017), arXiv preprint arXiv:1702.05812
 47. Nakamoto, S.: Bitcoin: A peer-to-peer electronic cash system (2008)
 48. Poon, J., Buterin, V.: Plasma: Scalable autonomous smart contracts. <http://plasma.io/plasma.pdf>
 49. Poon, J., Dryja, T.: The bitcoin lightning network: Scalable off-chain instant payments. <https://lightning.network/lightning-network-paper.pdf> (January 2016)
 50. Prihodko, P., Zhigulin, S., Sahno, M., Ostrovskiy, A., Osuntokun, O.: Flare: An approach to routing in lightning network. White Paper (2016)

51. Roos, S., Moreno-Sanchez, P., Kate, A., Goldberg, I.: Settling payments fast and private: Efficient decentralized routing for path-based transactions. In: 25th Annual Network and Distributed System Security Symposium, NDSS 2018, San Diego, California, USA, February 18-21, 2018 (2018), http://wp.internetsociety.org/ndss/wp-content/uploads/sites/25/2018/02/ndss2018_09-3_Roos_paper.pdf
52. Sivaraman, V., Venkatakrishnan, S.B., Alizadeh, M., Fanti, G.C., Viswanath, P.: Routing cryptocurrency with the spider network. CoRR **abs/1809.05088** (2018), <http://arxiv.org/abs/1809.05088>
53. Spilman, J.: Anti dos for tx replacement. <https://lists.linuxfoundation.org/pipermail/bitcoin-dev/2013-April/002433.html> (April 2013)
54. Wood, G.: Ethereum: A secure decentralised generalised transaction ledger
55. Wuille, P., Nick, J., Towns, A.: Taproot: Segwit version 1 spending rules. <https://github.com/bitcoin/bips/blob/master/bip-0341.mediawiki>
56. Zhao, L., Shuang, H., Xu, S., Huang, W., Cui, R., Bettadpur, P., Lie, D.: Sok: Hardware security support for trustworthy execution (2019)