Payment Channels Overview

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Abstract. This is an overview of the existing literature on virtual payment channels. Lightning [1], Perun [2] and TeeChan [3] are considered.

1 Introduction

Virtual payment channels are constructions that permit the secure exchange of assets between remote agents without the need for each transaction to be recorded in a global database. They are constructed in a way that either does not allow the agents to cheat (given appropriate assumptions), or give the opportunity to the cheated agents to report the latest valid state to a global database (i.e. blockchain) and reclaim their assets.

2 Lightning Network

This construction is the first to achieve a functional model for payment channels. It is designed for bitcoin and requires some new opcodes and removing the malleability of transactions to function properly [1].

1 Simple two-party channel

The basic construction is as follows. Suppose that *Alice* and *Bob* want to create a payment channel that contains 1 BTC consisting of 0.5 BTC from each party. To achieve this, they follow these steps (see also section 3.1.2 and Figure 4 in 3.3.2 in [1]):

1. Either party (say *Alice*) creates a "Funding" transaction (F) with an input of 0.5 BTC from her and 0.5 BTC from *Bob*, and a 2-of-$\{Alice, Bob\}$ multisig as output; she then sends F to *Bob*. This transaction is not yet signed nor broadcast. F needs to be signed by both parties to be valid.
2. *Alice* creates, signs and sends to *Bob* a "Commitment" transaction ($C1b$) that spends F and has the following outputs:

(a) 0.5 BTC that can be spent by *Alice* immediately when $C1b$ is broadcast.
(b) 0.5 BTC that can be spent by either party, but *Bob* can spend it only after a specified amount of blocks (say n) have been mined on top of $C1b$, whereas *Alice* can spend it only if *Bob* provides her with a "Breach Remedy" transaction (explained later) signed by him. This output is called "Revocable Sequence Maturity Contract" (RSMC).

Furthermore, *Alice* creates, signs and sends a "Revocable Delivery" transaction ($RD1b$) that pays the first of the two outputs of $C1b$ to *Bob*, but will be accepted by the network if it is in the mempool only after n blocks have been mined on top of $C1b$.
Bob similarly creates, signs and sends $C1a$ and $RD1a$ to *Alice*.

3. After *Alice* receives the signed $C1a$ and $RD1a$ from *Bob*, she verifies that they are both valid and correctly spend F. Given that everything works out right, she signs F and sends it to *Bob*.
Observe that she is not running the risk of *Bob* refusing to cooperate in signing F and thus keeping her 0.5 BTC locked because she has the ability to sign and broadcast the (already signed by *Bob*) $C1a$ and $RD1a$ and thus get her money back n confirmations after $C1a$ is confirmed (that is when $RD1a$ is confirmed). Thus *Alice* need not trust *Bob* in any way.
Bob similarly verifies that $C1b$ and $RD1b$ have the correct structure, along with *Alice*'s signature on F. He then signs F and broadcasts it. Note that he does not have to trust *Alice* either.

After initially setting up the channel, *Alice* and *Bob* can update it as follows (see also section 3.3.4 and Figures 7, 8 in [1]):

1. Both *Alice* and *Bob* follow exactly the same steps as before to create $C2a$, $C2b$, $RD2a$ and $RD2b$; the only difference these transactions have to their counterparts from the previous state of the channel is that, instead of 0.5 BTC for each player, they contain the new agreed balance of the channel (e.g. 0.4 BTC for *Alice* and 0.6 BTC for *Bob*).
2. *Alice* creates, signs and sends to *Bob* a so-called "Breach Remedy" transaction ($BR1a$). This transaction lets *Bob* redeem the RSMC output of $C1a$ as soon as $C1a$ is broadcast. *Bob* similarly creates, signs and sends $BR1b$ to *Alice*.

Note that this effectively disincentivises *Alice* from ever broadcasting $C1a$, since in such case *Bob* will have a window of n blocks during which he can claim the entire sum in $C1a$, 1 BTC, for himself. *Alice* had better

purge $C1a$ after $BR1a$ is sent to *Bob*. Similarly *Bob* is incentivised to refrain from ever broadcasting $C1b$.

This arrangement creates a situation where both players can be confident that the state of the channel is the one expressed by $C2a$, $C2b$, $RD2a$ and $RD2b$, thus they can assume that *Alice* has just paid *Bob* 0.1 BTC. No trust between the two players was needed all along. There are only two caveats: First, both players must periodically check the blockchain to ensure that the other party has not broadcast an old Commitment transaction. Second, in case of an uncooperative counterparty, one has to wait a prespecified amount of time before releasing their funds, which may be undesirable.

Thus, the necessary number of blocks mined on top of a Confirmation transaction for a subsequent Revocable Delivery to be valid (previously called n) must be carefully chosen in a way that does not lock up the funds for a long time in case of a dispute and at the same time does not require that the parties check the blockchain too often for a malicious broadcast of an already invalidated Commitment transaction.

Alice can outsource the task of the periodic check to a dedicated service by sending it all the previous Breach Remedy transactions. To incentivise the service to cooperate, *Alice* can pay a fee to it as an output of these transactions. Note that *Alice* does not need to trust the service, since the only thing it can do is to broadcast a Branch Remedy transaction that was created by *Alice*; she never discloses any of her private keys to it.

Finally, the parties can cooperatively close the channel without having to wait n blocks as follows: When both parties have agreed to closing the channel, *Alice* creates, signs and sends to *Bob* an "Exercise Settlement" transaction (ES) that spends the Funding transaction and has two simple outputs, each paying to the respective party the sum of the last agreed Commitment transaction. Following the previous example, this transaction would pay 0.4 BTC to *Alice* and 0.6 BTC to *Bob*. *Bob* can then also sign and broadcast the transaction to close the channel.

Once *Alice* has sent ES, she considers the channel as closed. If *Bob* does not broadcast ES, we have a dispute and she has to broadcast the latest Commitment transaction and wait for her funds to be unlocked.

2 Payments depending on preimage knowledge (HTLC)

Multi-hop payments can take place between players (e.g. *Alice* and *Dave*) who do not share a simple channel (i.e. an on-chain Funding transaction),

but share simple channels with intermediate nodes (e.g. *Alice* with *Bob*, *Bob* with *Carol* and *Carol* with *Dave*).

To enable the creation of multi-hop channels, so-called "Hashed Timelock Contracts" (HTLC) are used. An HTLC is an additional output in a Commitment transaction which can be redeemed by either *Alice* or *Bob*; *Alice* can redeem it after a specified number of additional blocks, say m, have been mined after the creation (*not* the broadcast) of the Commitment transaction, whereas *Bob* can redeem it at any time, but only if he produces the preimage R of a hash specified in the HTLC output (see also section 4.2 and Figure 12 in [1]).

More specifically, consider $C2a, C2b$ where, contrary to the example in the previous subsection, *Alice* has paid the 0.1 BTC to an HTLC instead of directly to *Bob*. *Bob* should be able to redeem the 0.1 BTC only if he knows the preimage R before the m blocks have been mined. In addition to $RD2a$ and $RD2b$, six additional transactions have to be signed and exchanged.

1. *Alice* signs and sends an "HTLC Execution Delivery" transaction ($HED1a$) to *Bob*. $HED1a$ pays the HTLC output of $C2a$ to *Bob*, only if he knows the required preimage R. Only *Bob* can broadcast the transaction.
2. *Bob* signs and sends a so-called "HTLC Timeout Delivery" transaction ($HTD1b$) to *Alice*. $HTD1b$ pays the HTLC output of $C2b$ to *Alice*, only after m blocks have been mined from the time $C2b$ was created. Only *Alice* can broadcast this transaction.
3. *Alice* signs and sends an "HTLC Execution" transaction ($HE1b$) to *Bob*. $HE1b$ pays the HTLC output of $C2b$ to *Bob*, only if he knows the required preimage R. Only *Bob* can broadcast this transaction. Its single output is an RSMC with duration n, spendable by *Bob*.
4. *Alice* signs and sends an "HTLC Execution Revocable Delivery" transaction ($HERD1b$) to *Bob*. This transaction spends the RSMC output of $HE1b$. *Bob* can broadcast this transaction after n blocks have been mined on top of $HE1b$.
5. *Bob* signs and sends an "HTLC Timeout" transaction ($HT1a$) to *Alice*. $HT1a$ pays the HTLC output of $C2a$ to *Alice*, only after m blocks have been mined from the time $HT1a$ was created. Its single output is an RSMC with duration n, spendable by *Alice*.
6. *Bob* signs and sends an "HTLC Timeout Revocable Delivery" transaction ($HTRD1b$) to *Alice*. This transaction spends the RSMC output of $HT1b$. *Alice* can broadcast this transaction after n blocks have been mined on top of $HE1b$.

Note that once again, no trust is necessary in the process described above. The RSMC outputs of $HT1a$ and $HE1b$ are necessary for future invalidation according to the "Breach Remedy" method. More details can be found in Figure 14 of section 4.3. In case of common desire to close the channel, they can be cooperatively closed using the "Exercise Settlement" method.

3 Multi-hop channels

With the use of HTLC outputs, it is possible to execute multi-hop payments as follows. Suppose *Alice* wants to pay *Dave* 0.001 BTC and they find out that they are connected through the preexisting channels $Alice \Leftrightarrow Bob$, $Bob \Leftrightarrow Carol$ and $Carol \Leftrightarrow Dave$. This payment can be completed with the following steps:

1. *Dave* generates a random number R and sends $hash\,(R)$ to *Alice*, *Bob* and *Carol*.
2. *Alice* and *Bob* update their channel with an e.g. 300-block HTLC that transfers 0.001 BTC from *Alice* to *Bob*.
3. *Bob* and *Carol* update their channel with an e.g. 200-block HTLC that transfers 0.001 BTC from *Bob* to *Carol*.
4. *Carol* and *Dave* update their channel with an e.g. 100-block HTLC that transfers 0.001 BTC from *Carol* to *Dave*.
5. *Dave* discloses R to *Carol*; he obtains 0.001 BTC from the 100-block HTLC transaction.
6. *Carol* discloses R to *Bob*; she obtains 0.001 BTC from the 200-block HTLC transaction.
7. *Bob* discloses R to *Alice*; he obtains 0.001 BTC from the 300-block HTLC transaction.

Thus *Alice* has paid *Dave* 0.001. No party can be defrauded: For example, *Carol* will pay 0.001 BTC to *Dave* if he shows her R within 100 blocks but then she can take the 0.001 BTC back by disclosing R to *Bob*; she has at least 100 more blocks to do so. In case *Dave* does not disclose R, all parties can take their funds back by settling on-chain.

On the other hand, assume that *Bob* does not cooperate after the establishment of the HTLC transactions, but keeps R hidden. In this case *Bob* will lose his 0.001 BTC to *Carol* and no other player will be negatively affected; *Carol* and *Dave* can fulfill their part without *Bob*'s cooperation, albeit *Carol* will have to wait for her channel with *Bob* to expire, since she has to settle on-chain. Likewise *Alice* can take back her

0.001 after the 300-block HTLC lock has expired. Thus no trust between parties is needed.

One can note two things: Firstly, there is no such thing as a persistent multi-hop channel. The whole procedure must be repeated for each subsequent multi-hop payment and the successful completion of one such payment does not facilitate the creation of future payments along the same route as far as the techniques described above are concerned. Nevertheless, previous cooperation between players can obviate the need of exploring the network anew for a connecting series of preexisting channels.

Secondly, all intermediate players have to actively engage for a multi-hop payment to go through. This means that a multi-hop payment's latency increases linearly with the length of the chain, as well as the waiting time if on-chain settlement is needed (given that the same margin of security is desired irrespective of the payment length). This reduces the scalability of the design and fosters the creation of centralized, heavily connected players that ensure that short chains are available instead of distributed, loosely connected players that exchange funds through long chains.

3 Perun

Perun [2] is a payment network designed for Turing-complete smart contract scripting languages. It has been implemented for Ethereum. Its main contribution is *multistate channels* that allow the dynamic deployment of virtual contracts, known as *nanocontracts*. Contracts of this type do not have to enter the blockchain if all parties are cooperative and only do so in case of a dispute.

The paper describes specifically the use of such multistate channels for creating virtual payment channels between parties that do not have a standard payment channel between them, but both have channels with an intermediary. Then the intermediary could substitute for the blockchain and thus a virtual payment channel on top of the two on-chain multistate channels can be created. The parties need the intermediary only for setting up the channel and to close it fast. If the intermediary refuses to close the channel, they can always fall back to the blockchain.

1 Payment channels

A basic payment channel is a tuple

$$\gamma = (\gamma.\texttt{id}, \gamma.\texttt{Alice}, \gamma.\texttt{Bob}, \gamma.\texttt{cash}, \gamma.\texttt{ver-num}, \gamma.\texttt{sign})$$

Versions of this tuple are held by *Alice* and *Bob*. γ.`id` is a unique identifier for the channel, γ.`Alice` and γ.`Bob` are the end-users of γ and γ.`cash` is a function from the end-users to a real non-negative value that denotes the amount of cash the user has in the channel. γ.`ver-num` is a number that is incremented with each channel update (so that the latest state of the channel is known in case of dispute) and γ.`sign` is the singature of the other party on (γ.`id`, γ.`cash`, γ.`ver-num`).

A payment channel has a corresponding $\texttt{PaymentContract}_{\gamma.\texttt{id}}$ on the ledger. End-users interact with the contract only to set up and close the channel, whereas updating the channel happens off-chain. The contract does not contain the fields γ.`ver-num` and γ.`sign`; the two fields are kept only by the end-users.

2 Multistate channels

A basic multistate channel is a tuple

$$\gamma = (\gamma.\texttt{id}, \gamma.\texttt{Alice}, \gamma.\texttt{Bob}, \gamma.\texttt{cash}, \gamma.\texttt{nspace})$$

References

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