Nitro Protocol

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1 Motivation

A blockchain is a device that enables a group of adversarial parties to come to consensus over the contents of a shared ledger, without appealing to a trusted central authority. Whether using a proof-of-work or a proof-of-stake algorithm, this process has a cost both in terms of time and in terms of money. For the Ethereum blockchain, this cost results in an effective limit of around 15 transactions per second being processed on the network. When compared with the visa network, which can process on the order of 50,000 transactions per second, this limit supports the view that blockchains, in their current form, do not scale.

State channels offer a solution to the blockchain scaling problem. A state channel can be thought of as a set of updatable agreements between a fixed set of participants determining how a given set of assets should be split between them. The agreements are updated off-chain through the exchange of cryptographically signed messages between the participants according to some set of previously-agreed update rules. The assets in question are held in escrow on the blockchain, in such a way that they can only be released according to the latest agreement from the state channel. If the off-chain cooperative behaviour breaks down, for example if one party refuses to sign updates either by choice or due to unavailability, any of the parties can reclaim their share of the assets by presenting the latest agreement to the chain. An exit game is required to give other parties the opportunity to present a later state, but all parties have the guarantee that they can reclaim their share of the funds within some finite time.

In addition to the increased throughput, state channels bring instant finality to transactions: the moment a channel update is received the participant knows that the assets transferred are now assigned to them. They cannot access the assets immediately but they have the power to prevent any other party claiming those assets in the future. The only requirement is that participants need to be live enough to engage in the exit game if an opponent attempts to exit an earlier state. In practice, the requirement here is to check the chain periodically

- at time intervals that are less than, but on the same order of magnitude as, the challenge duration in the exit game.

As the channel updates are created and exchanged off-chain, the channel-update throughput is limited only by the speed of constructing, signing and broadcasting the update. Given that channel updates only needed to be communicated between participants and the system is therefore highly parallelizable, it is difficult to put a bound on the total transaction throughput of a system of state channels. In practice the system is only limited by the on-chain operations required to move assets when opening and closing channels.

In this paper, we allow channels to be opened and closed off-chain. We enable the construction of efficient state channel networks.[TODO]

2 Existing work

Lightning and raiden - payment channel networks - directional

Celer - directional but with multiple paths - general conditions

Perun - virtual payment channels (different from HTLCs) - but using a validity time - and then state channel networks - constrained [Connext - have removed the time limit with a trade-off of trusting the hub - TODO: check this]

Counterfactual - thinks about counterfactual instantiation - also app instance on top, which we collaborated on - possible to do meta-channels, but the details are not given in the paper and are still being finalized

Our contribution: - like perun without the time limit Unconstrained subchannels

3 State Channel Concepts

- describe the setup and fundamental logic that allows us to reason about state channels - what it means for two states to be equivalent - how we can safely move between equivalent states without exposing either participant to risk

- abstract away a lot of the details - ForceMove centric but believe that the ideas presented here, in some form, are present in most frameworks - draw examples from ForceMove: turn based, programmable by specifying libraries

- signature scheme - hash

3.1 State Channel Systems

- in this paper we will deal with systems of interacting state channels - it will be useful to start by looking at some of the parameters that give these systems their characteristics - in particular we will look at three important parameters: the space of participants, the space of assets and the application rules

- consider a state channel system (Participants, Assets, ApplicationRules)

- space of participant addresses - all addresses generated from the signature scheme - someone somewhere should know the private key corresponding to a participant address - they are the owner of that address - a participants can own multiple addresses - the key is used to sign updates - addresses don't have to have any funds allocated on-chain - they can be ephemeral

- space of channels - ordered subset of participants - a nonce - channel address - non-collisions

- space of assets - allowed values these can take - in this paper we deal with a single asset which we will refer to as coins - the assets allocated can be summarised with a single integer - in this paper we allow the coin value to take any value in $\mathbb{Z}$ - this is not realistic for the blockchain context, where there is typically a maximum value, `MAX`, after which totals overflow - meaning that we should really consider coins in the space $\mathbb{Z}_{\texttt{MAX}}$ - in ethereum $\texttt{MAX} = 2^{256} - 1$ - we can also consider state channels that operate on multiple assets: $\mathbb{Z}_{\texttt{MAX}} \times \mathbb{Z}_{\texttt{MAX}}$

- space of application rules. Consider these to also define the states - state transitions - payment channel can be thought of in terms of a state channel system with a single application - is it possible to add to the space of application rules - what sort of rules does it support? transition rules depend on time or the general state of the chain - we assume here that they don't - possible to remove these restrictions

- space of channel addresses - participant addresses - channels = set of participants + nonce - channel addresses

3.2 Funding and Channel Outcomes

- adjudicator: two important collections - funds held and outcomes - holding funds + notation - holding outcomes

- outcomes of a channel - outcome: how funds should be distributed - notation - make this precise later

- ways of registering outcomes in force move - only one outcome on-chain for each channel. Once one outcome has been registered no other one can be - abstract a channel to be something that can reach an outcome

- first part of this is what outcomes you can register on-chain

3.3 Finalizable and Enabled Outcomes

- state of a channel - outcome is finalizable if you can register it on-chain and no-one can stop you. - an unbeatable strategy for getting it on-chain - series of actions

Example 3.1. The next mover in ForceMove. In a ForceMove state channel with n participants, if participant p has just received state σ_m with $m > n$ and it is their turn to sign state $m + 1$, then we have $[\sigma_m.\beta]_p$ - the state's balances $\sigma_m.\beta$ is a finalizable outcome for p. Why? To finalize this outcome p can call a force-move on σ_m and then fail to respond within the timeout. [The reason why ForceMove always allows a transition to a conclude state is to give p a way of accomplishing the same outcome off-chain.]

Example 3.2. Two conclusion proofs. In a ForceMove state channel, if two different conclusion proofs with different outcomes, $\beta_1 \neq \beta_2$, are both held by participants p_1 and p_2, then no outcome is finalizable by any participant. Why? No finalizable outcome other than β_1 is possible any party p, as it is always possible for either p_1 or p_2 to register the conclusion proof resulting β_1 immediately. But the same is also true for β_2. Therefore no finalizable outcome exists. [For this reason, participants should never sign more than one conclusion state.]

- enabled outcomes

Example 3.3. Pre-fund setup in ForceMove. In a ForceMove state channel with n participants P, at end of the pre-fund setup i.e. when the last state to be broadcast was σ_n, then we have $[\sigma_n.\beta]_P$ - the state's balances $\sigma_n.\beta$ is finalizable for all participants of the channel. Why? According to the ForceMove transition rules, the outcome must remain unchanged for the first $2n$ states. That means that every participant must contribute another signature before the outcome of the state can change. By with-holding this signature and forcing the channel to conclusion through a series of force-moves, any participant can ensure that the current outcome is registered on-chain.

3.4 Calculating Value

- system: related channels + adjudicator - value (unbeatable strategy for extracting at least a given total, without assuming we add funds) - value equivalent (if two system states have the same value) - value preserving transition - applications change value, opening and closing an application shouldn't

- transitioning between outcomes - rewrite rules - channels update independently

- possible to transition between finalizable states

4 Turbo Protocol

Turbo protocol allows a set of participants who already have a funded channel to open and close sub-channels without any on-chain transactions.

- protocol really specifies the format of the channel outcomes and how they're interpreted on-chain - can be combined with force-move to provide a full functioning state channel system

As an example, suppose Alice and Bob want to play a game of chess and that they already have an existing state channel, χ_L, which holds 5 of Alice's coins and 5 of Bob's. 2 coins from the loser.

Ledger Channel [v1]	
Alice	5
Bob	5

They decide that winner of the chess game should win 2 coins from the loser and proceed by creating a new channel χ_C for the chess game with the appropriate starting state. They then update χ_L to allocate funds to these games.

Ledger Channel [v2]	
Alice	2
Bob	2
Chess	4

Chess [v1]	
Alice	2
Bob	2

Once the funds are allocated, they are free to play the game of chess. Updates to the chess channel are independent from updates to χ_L and to any other sub-channels that are potentially funded by it. Alice wins the chess game, so the final state in the chess channel allocates all the funds to her.

Ledger Channel [v2]	
Alice	2
Bob	2
Chess	4

Chess [FINAL]	
Alice	4
Bob	0

To close the chess channel off-chain, Alice and Bob update the state of the ledger channel to absorb the outcome of the game.

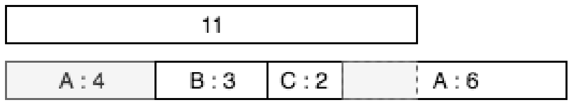
Ledger Channel [v3]	
Alice	6
Bob	4

In the rest of this section we will present the protocol that makes the above interaction possible.

4.1 Turbo Outcomes

The key difference between Turbo and ForceMove is that Turbo allows the outcome of a channel to allocate funds to other *channels*, as well as to the participants.

Interpretation and manipulation of the outcomes when they exist on-chain. Registering those outcomes is done by ForceMove.

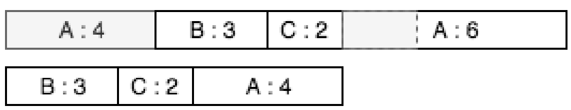


overlap(A, { A: 4, B: 3, C: 2, A: 6 }, 11) = 6

```
def overlap(recipient, outcome, funding):
  result = 0
  for [address, allocation] in outcome:
    if funding <= 0:
      break;

    if address == recipient:
      result += min(allocation, funding)
    funding -= allocation

  return result
```



remove(A, { A: 4, B: 3, C: 2, A: 6 }, 6) = { B: 3, C: 2, A: 4 }

```
def remove(outcome, recipient, amount):
  newOutcome = []
  for [address, allocation] in outcome:
    if address == recipient:
      reduction = min(allocation, amount)
      amount = amount - reduction
      newOutcome.append([address, allocation - reduction])
    else:
      newOutcome.append([address, allocation])

  return newOutcome
```

We will now introduce the three on-chain operations that drive Turbo: deposit, withdrawal, and transfer.

The **deposit** operation is used to increase the funds held for a given channel. In order for the operation to be valid it must be accompanied by a transfer of funds equal to the increase.

$$D_X(x)[\![\alpha_X(y)]\!] = [\![\alpha_X(x+y)]\!]$$

The deposit can be called by anyone but a rational participant, p, should only make a deposit of size x if it causes the value of the system state for p to increase by x.

The **withdrawal** operation is used to withdraw funds held at a given address, A, by a party with a knowledge of the corresponding private key. If $x \leq x'$ then

$$W_A(x)[\![\alpha_A(x')]\!] = [\![\alpha_A(x'-x)]\!]$$

In the above equation, we focus only on the affect of the withdrawal operation on the system state. In practice the withdrawal should also specify the external address that the funds should be sent to along with the signature. A potential method signature is `withdraw(fromAddr, toAddr, amount, signature)`, where `signature` is A's signature of the other parameters [1]. Note that the signature requirement coupled with the no-collision assumption means it is not possible to withdraw from the funds held for a channel.

The **transfer** operation, $T_{A,B}(x)$, is an instruction to transfer funds currently allocated to address A to address B, according to the outcome of channel A.

```
from overlap import overlap
from remove import remove

def transfer(recipient, outcome, funding, amount):
  if overlap(recipient, outcome, funding) >= amount:
    funding = funding - amount
    outcome = remove(outcome, recipient, amount)
  else:
    amount = 0

  return (amount, outcome, funding)
```

If channel X holds x and the outcome of X allocates y to Y within x. - then update channel X to hold x, channel Y to hold y, and decrease the amount X allocates to Y by y

For example,

$$T_{A,B}(3)[\![\alpha_A(10)\beta_A(B:3,C:7)]\!] = [\![\alpha_A(7)\alpha_B(3)\beta_A(C:7)]\!]$$

[1] In practice, we can add the `senderAddress` to the parameters to sign, in order to prevent replay attacks.

4.2 Value Equivalence in Turbo

- transfer operations commute - value equivalent in terms of α_A - if I can find one set of transfer operations they're equivalent

- funding a ledger channel - only deposit if it increases your value by the deposit amount - opening a subchannel

4.3 Examples

While this generalization allows for a variety of relationships between different channels, we will focus here on a setup where a single parent channel funds one or more sub-channels [2]. Following the Perun paper, we will refer to this parent channel as a **ledger channel**.

- ledger channel is assumed to be running the consensus application

4.3.1 Opening a sub-channel

- make precise the operation we performed in the introduction, where we opened a subchannel - here the enforcable state for χ is assumed to be the ready-to-fund state - doesn't matter what application is running in the channel - just what the initial balances are

$$
\begin{aligned}
S_1 &= [\![\alpha_L(a+b)]\!] \quad [\beta_L(A:a, B:b)]_{A,B} \\
S_2 &= [\![\alpha_L(a+b)]\!] \quad [\beta_L(A:a, B:b)]_{A,B} \quad [\beta_\chi(A:a', B:b')]_{A,B} \\
S_3 &= [\![\alpha_L(a+b)]\!] \quad [\beta_L(A:a-a', B:b-b', \chi:a'+b')]_{A,B} \quad [\beta_\chi(A:a', B:b')]_{A,B}
\end{aligned}
$$

- at each point it is value equivalent for both A and B to a b respectively - each step only changes one channel at a time - therefore we can do by single-channel-rewrite lemma

4.3.2 Closing a sub-channel

- closing a subchannel is similar - hear the finalizable state is assumed to be a conclude state from the end of the channel

$$
\begin{aligned}
S_1 &= [\![\alpha_L(x)]\!] \quad [\beta_L(A:a, B:b, \chi:a'+b')]_{A,B} \quad [\beta_\chi(A:a', B:b')]_{A,B} \\
S_2 &= [\![\alpha_L(x)]\!] \quad [\beta_L(A:a+a', B:b+b')]_{A,B} \quad [\beta_\chi(A:a', B:b')]_{A,B} \\
S_3 &= [\![\alpha_L(x)]\!] \quad [\beta_L(A:a+a', B:b+b')]_{A,B}
\end{aligned}
$$

where $x = a + a' + b + b'$. - the analysis is exactly the same as in the opening case

[2] Note that we allow the case where the sub-channels are themselves ledger channels.

4.3.3 Topping up a ledger channel

- useful to be able to top up without disturbing sub-channels supported in a ledger channel - topping up is similar to depositing in force-move

$$
\begin{array}{ll}
S_1 = [\![\alpha_L(x)]\!] & [\beta(A:a, B:b, \chi:c)]_{A,B} \\
S_2 = [\![\alpha_L(x)]\!] & [\beta(B:b, \chi:c, A:a+a')]_{A,B} \\
S_3 = D_L(a')[\![\alpha_L(x)]\!] & [\beta(B:b, \chi:c, A:a+a')]_{A,B} \\
S_4 = [\![\alpha_L(x+a')]\!] & [\beta(B:b, \chi:c, A:a+a')]_{A,B}
\end{array}
$$

- rearrange the current outcome to put the depositor last - note that $\nu_A(S_3) - \nu_A(S_2) = a'$ as it should be if A is to deposit

4.3.4 Partial checkout from a ledger channel

- partial checkout is the opposite to top up - the scenario here is two parties have a ledger channel open, supporting one or more subchannels - participant A wants to be able to withdraw - this means we need to increase the value of α_A - we will assume here that we start with $\alpha_A(0)$

$$
\begin{array}{lll}
S_1 = [\![\alpha_L(x)]\!] & [\beta_L(B:b, A:a, \chi:c)]_{A,B} & \\
S_2 = [\![\alpha_L(x)]\!] & [\beta_L(B:b, A:a, \chi:c)]_{A,B} & [\beta_{L'}(B:b, A:a-a', \chi:c)]_{A,B} \\
S_3 = [\![\alpha_L(x)]\!] & [\beta_L(L':x-a', A:a')]_{A,B} & [\beta_{L'}(B:b, A:a-a', \chi:c)]_{A,B} \\
S_4 = [\![\alpha_L(x)\beta_L(L':x-a, A:a')]\!] & [\beta_{L'}(B:b, A:a-a', \chi:c)]_{A,B} & \\
S_5 = [\![\alpha_{L'}(x-a')\alpha_A(a')]\!] & [\beta_{L'}(B:b, A:a-a', \chi:c)]_{A,B} &
\end{array}
$$

- technique here is to create a replacement ledger channel with the updated totals and then update the original channel to point here. - in transitioning to S_4 we take L to the chain. probably using conclude to avoid the timeout

5 Nitro Protocol

- extension to turbo. introduce a different type of outcome. allows us to support channels through a third party - call these virtual channels

- example: suppose that Alice wants to play chess with Bob - doesn't have a ledger channel open but they both have a channel open with Hugo

- how this enables a hub

- how this enables multi-hop routing

5.1 Outcomes in Nitro

- extends turbo by adding a new type of outcome (and a new type of channel)
- refer to this as the guarantee and write this γ

- guarantee outcomes + on-chain operation

- construction

- opening + closing

6 Acknowledgements

- Andrew Stewart - James Prestwich - Chris Buckland - Magmo team

7 Appendix

7.1 Overview of ForceMove

7.2 The Consensus Game

7.3 Virtual Channels on Turbo

7.4 Payouts to Non-Participants

7.5 Possible Extensions