

zkSwap - Scaling Decentralized Exchanges through Transaction Aggregation

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1 Introduction

When being launched in 2015, Ethereum [12] set out to change the way we compute. A trustless, permissionless, and decentralized world computer was envisioned, set to open a new class of applications. The importance of running verifiable, Turing-complete code in a permissionless and trustless manner cannot be overstated and enables products and services not thought to be possible. However, the technical limitations have also become apparent quickly. Computations are expensive, theoretical transactions per second are low, and the overall throughput has been stagnant. While Eth2 gives a path towards scaling the network, it is expected to take years to complete.

The first major use case for Ethereum was tokenization. With the development of the ERC-20 standard, launching a token on the Ethereum blockchain was trivial. As tokens run as smart-contracts on the Ethereum blockchain, they are secured by its proof of work consensus, which, given Ethereum's PoW hash rate, makes consensus attacks infeasible. Running on Ethereum blockchain is a significant benefit when looking to tokenize things, as network

security can be assumed. While tokenizations are a step in the right direction, they do not come close to the initial vision. While the standardization enables simple integrations into exchanges and wallets, most tokens are isolated in their functionality and ecosystem and lack productive usage.

With all of these developments over the past couple of years, it seems we have now entered a new phase of smart-contract use-cases, namely Decentralized Finance (DeFi). While DeFi has many different products and functionalities, at its core aims to utilize tokenized assets in some productive form.

Lending and collateralized borrowing is possible with Aave [10], assets can be deposited into liquidity pools[2] to generate yields, flash-loans [10][2] enabled uncollateralized borrowing as long as the loan is repaid in the same transaction and assets can be traded in a non-custodial way with Uniswap [2]. It can be questioned how useful or necessary these protocols really are, but the core idea behind them is impressive. Rebuilding traditional financial products, running as non-custodial and permission-less smart-contracts, all based on the same standardizations, has the potential to reshape the way finance works. With these developments not looking to slow down, they are quickly overwhelming the Ethereum blockchain, pushing transaction costs [8] higher and higher.

One of these new DeFi applications is Uniswap [2]. Uniswap is a crypto-asset exchange running as a collection of smart-contracts on the Ethereum blockchain, enabling non-custodial, trust-less, and permission-less trading of ERC-20 assets. Since its running on the Ethereum Blockchain, reducing the computational complexity of trade execution is essential for making it a viable product. In typical crypto-asset exchanges, trading is built around a central order book. Users can add buy or sell orders for a given trading pair, and a matching engine checks if these orders can be matched, executing the trade once they do. While running this on modern server infrastructure is feasible, running it on the blockchain is not. The demand for memory and processing power is too large, so a different approach must be taken. Uniswap solves this by applying the automated market maker (AMM) model, which will be explained in detail in sec. XX. By applying this model, Uniswap reduces the computational complexity to make this a viable business model. At least it was, when Uniswap launched.

The recent rise of Ethereum's gas price [8] can also be attributed to the growing popularity of Uniswap. Currently, it is one of the most used smart-contract on the Ethereum blockchain, making up on average around 15% of gas [7] usage of a block at the time of writing. To date, it accrued over \$280 million in transaction fees [9] and has settled over \$100 billion in trading volume [1]. With the gas price having reached 500 gwei on a couple of occasions, a single Uniswap trade can cost upwards of \$130. While it would be assumed that high gas prices cause a reduction in trading volume, the opposite is the case. As shown in F.1 there seems to be a strong correlation between daily trading volume on Uniswap and the average daily Ethereum gas price, so re-

token all isolated,
not working to-
gether... Not a lot
of gas needed blabla

Mention other swap
protocols?

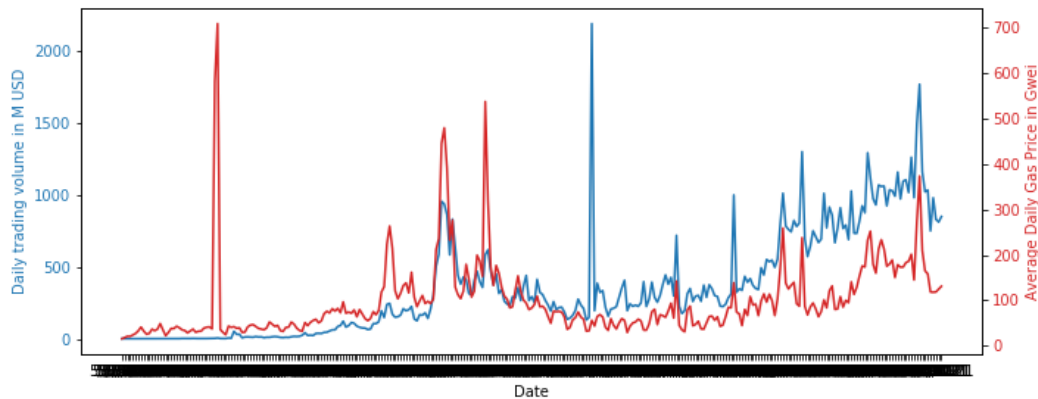


Figure 1: Combined daily Uniswap trading volume in million USD and average daily Ethereum gas price

ducing gas consumption by Uniswap transactions should result in a reduced gas price for the entire network.

With longer-term scaling solutions in development but still years away, a shorter-term solution is needed. A couple of short-term scaling approaches have been proposed. While these do differ, they all aim to move transactional data to a layer-2¹ system, while ensuring correctness of that data in some way. One of the approaches is called zk-rollup, the focus of this work. Moving data to a layer-2 system can increase the number of transactions that fit into a block while also reducing transaction costs for the user, which is beneficial for Uniswap users and all other participants of the Ethereum network.

Current zk-rollup enabled applications running on the Ethereum mainnet, one of them being ZK Sync, are focused on reducing cost of Ether and ERC-20 transfers. Users deposit funds into its smart-contract, which results in the user's deposit being represented as balance in layer-2. When a user makes a transfer to another user, the involved balances get updated in layer-2, while the correctness of these updates is ensured via zkSNARK. It is important to note, that ZK Sync acts as a closed system, transfers only change balances in layer-2, while deposited funds in the smart-contract do not move. While this approach has significantly reduced costs of transfers, it only marks the first generation of potential(?) zk-rollup enabled apps.

not a great sentence

Aggregating Uniswap trades is an interesting application to explore the potential of zk-rollup technology. It combines the layer-2 storing and updating of balances already done by ZK Sync while opening the system to interact with other smart-contracts. When aggregating trades, we need to interact with the Uniswap contracts to execute the aggregated trade, then update the layer-2 balances according to the trade and verify everything via zkSNARK. It is the next step in exploring the potential of zk-rollups as a generalizable

¹A layer-2 system is a data storage that does not reside on the blockchain but has its state committed to it in some way

scaling solution, applicable to any kind of smart-contract.

2 Background

2.1 Plasma, Optimistic Rollup and zkRollup

2.2 Data Availability

2.3 layer-2

2.4 Merkle Trees

2.5 mimc

2.6 Replay Attacks

A common security consideration to make in cryptographic protocols are replay attacks. A replay attack occurs when a valid cryptographic proof is maliciously resubmitted, and no security checks are in place to invalidate the resubmission. When making a transaction in a blockchain network, the transaction is signed with the user's private key. Miners that receive transactions check the signature's validity, which authorizes the transaction as the user has access to the address's private key. However, a malicious actor could store these signed transactions and resubmit them to the network. Since the signature is still valid, a mechanism is needed to invalidate transaction signatures, once they have been included in a block and thereby executed. In most blockchain systems, like Bitcoin or Ethereum, this is solved by tracking a nonce for each address. Miners extract an address's current nonce by indexing the entire blockchain, simply counting the number of confirmed transactions. Among other things, the nonce is part of the signed transaction. When a miner checks the signature, it is also checked if the nonce set in the signed transaction has been incremented by one, when comparing with the nonce that was extracted. This invalidates a resubmission of the signed transaction and prevents replay attacks.

Transaction Replay Attacks in zkSwap The way transactions are executed in this system is quite different, compared to the blockchain systems described above. As we will explore, most verifications and computations happen off-chain and are then verified on-chain with a single proof, that

When making a transaction, which can be a trade, a deposit or a withdrawal, a user signs the transaction details and sends them to our off-chain entity, the aggregator. The signature is then checked in a zkSNARK circuit, along with the nonce. The resulting proof can then be used to verify the correct execution of the zkSNARK circuit, as an effect verifying the correct. While the signature check happens off-chain, the mechanism of preventing replay attacks is comparable to most blockchain systems. By checking if the

nonce signed in the transaction details has been incremented, we ensure the signed transaction is invalidated when resubmitted.

Proof Verification Replay Attacks Another consideration to make, is the submission and verification of the zkSNARK proof. It also could be resubmitted, thereby breaking the protocol if no measures are in place to prevent this. When verifying a zkSNARK proof, we're essentially proving the execution of the circuit was done correctly, and that the resulting outputs were computed by running the circuit. In this system, the zkSNARK circuit is used to ensure correct state transitions tbc

2.7 zk-SNARKs

2.8 gas amount vs gas price

3 Approach

The goal of the work is to explore if zk-rollups can be used to aggregate Uniswap trades in an effective manner. The prototype is able to aggregate trades for a single trading pair, Ether and an ERC-20 token of choice. First, we'll look at the systems design to understand how the different entities work together.

The system consists of two main entities that are required for it to function. The first entity to look at, is the on-chain entity, we call zkSwap. zkSwap is a smart-contract deployed on the Ethereum blockchain and has three main jobs, verifying deposit and withdraw batches, processing instant withdraws and verifying trade batches. It holds users funds and exposes the on-chain functionality, to the user and emits balance updates.

The second entity to look at is the aggregator. The aggregator consists numerous systems, both off-chain and on-chain, and is mainly tasked with receiving deposits, withdraws or trade orders, aggregating and executing them, and then verifying them with the zkSwap contract. The aggregator stores a merkle-tree of users balances and keeps it in sync by listening for events emitted by the zkSwap contract.

3.1 Design

In this section we will explore the design of the system, looking at the different functionalities and dependencies to understand the core mechanics of how the different entities interact with each other.

The two main entities of this system are the zkSwap smart contract and the aggregator.

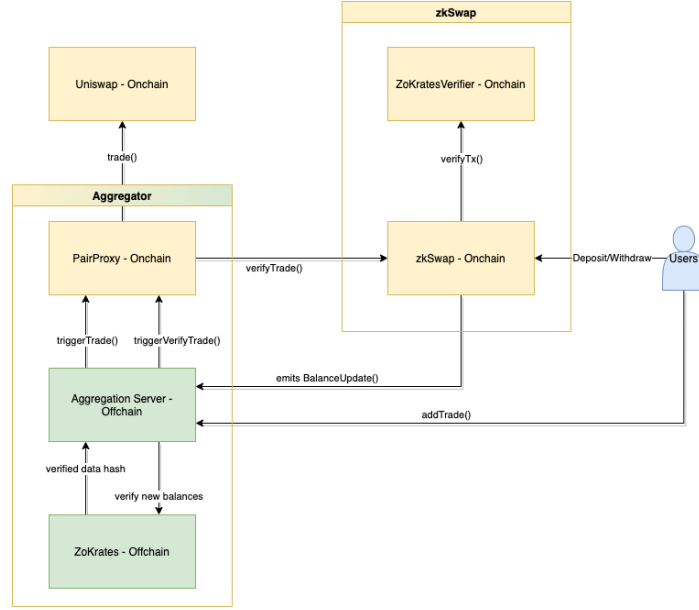


Figure 2: High level architecture of the system

3.1.1 zkSwap Smart-contract

The zkSwap contract, is the core entity the user interacts with. Its a smart-contract, that from the users perspective, is mainly used for depositing and withdrawing funds in our system and keeping track of user balances.

Deposits To use the system a user first has to deposit funds into the smart-contract. The funds need to be sent as a normal on-chain transaction to the smart-contract, where they will be stored, while the balance is then represented in layer-2. To deposit funds, a user calls the deposit function in the zkSwap smart-contract and adds the funds to be deposited to the transaction. When the funds have been received, an event is emitted informing the aggregator about the new deposit. At the same time, the user signs the deposit data, and sends it to the aggregator as a message. The aggregator aggregates a number of deposits, verifies the correctness in the zkSwap smart-contract, at which point they will show up as balance for the user.

Withdraws When withdrawing funds, the user needs to decide between an aggregated withdraw, similar to the deposit, or an instant on-chain withdraw. The aggregated withdraw works just like the deposit, only difference being the a withdraw amount is specified instead of sending funds. After the aggregation is complete, the user will receive the funds as an on-chain transaction. A user can also withdraw funds by using the instant withdraw feature. While it costs significantly more gas to withdraw funds with this function, it can be used without the aggregator being online. This protects the user from not

being able to withdraw its funds in case the aggregator is offline or has turned malicious.

Verification of Aggregated Trades The last main functionality of the zkSwap contract is the verification of aggregated trades. Once the aggregator has completed the aggregation batch, it send the new balances along with a zkSNARK proof and the traded funds to the zkSwap contract. If the proof is valid and the correct amount of funds have been sent to the zkSwap contract, the new balances are emitted, finalizing the state. The aggregator is now refunded, receiving the funds it spent when executing the aggregated trade on Uniswap.

3.1.2 Aggregator

As the name implies, the aggregators job is aggregating deposits, withdraws and trades. It facilitates the aggregation of these operations and is built in a way that ensures correct execution, while no trust assumptions are made. The aggregator relies on a number of different systems to function, in the section we look at it from a functional perspective, explaining the core functionalities and what systems is relied on. This will be explained in the implementation section in more detail.

Deposits and Withdraws When a user deposits or withdraws funds, choosing the aggregated type, the user sends a signature of the deposit/withdraw operation to the aggregator. The aggregator receives theses messages, collecting them as the next aggregation batch. Once a number of messages have been received, the new balances are calculated and passed to the corresponding ZoKrates program, where the correctness of the balances and signature is checked. If this is successful, a zkSNARK proof object is created. The aggregator now send the proof, along with the new balances to the zkSwap smart-contract. If the proof is valid, the new balances are emitted by the zk-Swap contract. Each withdraw will now be credited by sending the requested funds to the users.

Aggregating Trades A user can make a trade by sending a message to the aggregator. Similarly to deposits and withdraws, the aggregator collects messages as the next aggregation batch. All received trade messages are now aggregated and offset internally, resulting in the 'net-trade' that must be executed to honor all trades of the batch. The 'net-trade' is then sent to the 'PairProxy' smart-contract as a on-chain transaction, which in turn will execute it on Uniswap. The details and reasoning of this contract will be explained in the implementation section. Once the trade is executed, the new balances are calculated and the correctness ensured by using the corresponding ZoKrates program. The resulting proof and the new balances are sent to the PairProxy smart-contract. The previously purchased funds are

now added to the transaction, forwarding it to the zkSwap smart-contract. The proof is verified, the new balances emitted, and the aggregator is refunded the amount paid in the 'net-trade'.

Storing Balances in a Merkle Tree The aggregator keeps track of the balances by listening to events emitted by the zkSwap smart-contract. When an event is received, the balance is either updated or added to the merkle tree if it's a new user. Since the events stay on-chain, the merkle tree can always be rebuilt by querying these events, and updating the merkle tree sequentially. The aggregator provides endpoints where balances can be queried, along with the corresponding merkle paths, which are used throughout the system. It is important to remember, that the balances are public and can be queried by anyone.

PairProxy Smart-contract This smart-contract is controlled by the aggregator and is used to execute trades on Uniswap and forward transactions to the zkSwap smart-contract. The aggregator can use it to hold funds, which makes the transactions cheaper.

3.2 Implementation

In this section we will look at the way these functionalities are implemented and how they function.

3.2.1 Storing and Updating Balances

Balances are represented as a balance object in our system. This object consists of four fields that are necessary to represent balances correctly, the `ethAmount`, the `tokenAmount`, the users address and a nonce. It is important to understand the core technique used to store and update balance objects before we look at the different functions that trigger them. We want to make balance object updates as cheap as possible, while not relying on any external data availability. Essentially, this means that we need to store the balances on-chain. Storing data on-chain is typically very expensive. It is important to make a distinction between storing data in a smart-contracts runtime and storing data in the event log. Both methods of storage are on-chain, using the event log is significantly cheaper though. A disadvantage of using the event log however, is the fact that it can't be accessed from a smart-contracts runtime, and must be queried by a client. This solves the external data availability problem. We can store balances cheaply by emitting the 'BalanceUpdate' event, without relying on other systems to stay online. A client can query the event log, gather the required data and pass it as parameters to the transaction. However, we now need a mechanism to ensure, the user is passing correct data.

Merkle Trees We can achieve this, by using a merkle tree [11]. Merkle trees are a suitable data structure, as the merkle root represents the entire tree state in a highly compressed form, while proving a leaf's inclusion in the tree can be done with $O(\log n)$. This is ideal for our use-case. Every balance is stored as a leaf in a merkle tree, running in layer-2. The merkle tree is built and kept in sync by subscribing to the 'BalanceUpdate' event emitted by our smart-contract. A client can query balances from this tree, receiving the valid merkle path along with the balance object. The correctness of that data can be proven by recreating the merkle root, which is stored and updated in the zkSwap smart-contract. Since all changes in balance are committed by emitting the 'BalanceUpdate' event, it must be ensured that the merkle root is changed according to the updated balance. It is important to understand, that the only way balances can be updated is with the 'BalanceUpdate' event.

3.2.2 Aggregating Balance Updates

Updating a user's balance is at the core of this system. Deposits result in a balance update, as do trades and withdrawals. Before looking at these in detail, it is important to understand how balance updates can be aggregated, reducing the transaction costs for these operations. Since balances are stored in a merkle tree, we can ensure the correctness of a balance by running an inclusion proof. However, running this in a smart-contract is expensive, as a lot of hashing is required. To reduce this cost, we can ensure the correctness by running this in a ZoKrates program. If the ZoKrates program exits successfully, a zkSNARK proof is generated, which can be used to verify our execution on-chain.

Merkle Inclusion Proofs In order to ensure the correctness of balance updates, we first need to verify the inclusion of the balances involved in the merkle tree. Doing this one by one is simple. Every balance provides its merkle path which it can be hashed with. If the resulting hash matches the current merkle root stored in the zkSwap smart-contract, we can be assured the provided balance is included in the tree. At the same time, this enables us to reuse the merkle path for updating the balance. We can simply change the balance's values after passing the inclusion proof, rehash with the merkle path, and the result is the correct root for the updated balance leaf. Since the majority of hashing is done in ZoKrates programs, looking for a hashing function that can efficiently be executed in a zkSNARK circuit is important. At the same time, we also want the hashing function to be somewhat affordable when executing in the smart-contract. In this implementation we will utilize the MiMC [3] hashing function, as it can be used in zkSNARK circuits efficiently. The MiMC function is used with the feistel structure and setup with 220 rounds, which is deemed secure. The merkle tree is hashed with the MiMC hashing algorithm.

Chaining Inclusion Proofs When dealing with multiple balances, the inclusion proof can be done the same way. Every balance provides its merkle path, the resulting hashes should be the same for each balance. Things become more difficult when updating the balances. Updating the first balance in the batch now invalidates the merkle path of all following balances. In order for this to work, the merkle paths for each balance must be created sequentially. This can be solved by sorting the balances before hand, and generating each merkle path based on the changes of the previous balance. The new root of the first balance is the old root of the next balance. This can be chained to an infinite length and results in a constant number of hashes required for each balance update. The last hash to be computed is the new merkle root, representing all balance updates.

Algorithm 1: Chained merkle inclusion proofs for verifying and updating balances

```

1 function verifyAndUpdateMerkle;
   Input : oldBalances[], newBalances[], merklePaths[], root
   Output: newMerkleRoot
2 foreach oldBalances do
3   | assert(computeRoot(oldBalances[i], merklePaths[i]) == root)
4   | root ← computeRoot(newBalances[i], merklePaths[i])
5 end
6 return root

```

Algorithm 2: Computes merkle root of given parameters

```

1 function computeRoot;
   Input : balance, merklePaths[]
   Output: root
2 computedHash ← MiMC(balance)
3 foreach merklePath do
4   | if merklePath[i][0] = 0 then
5   | | computedHash ← MiMC(computedHash, merklePath[i][1]);
6   | else
7   | | computedHash ← MiMC(merklePath[i][1], computedHash);
8   | end
9 end
10 return computedHash

```

The merkle path has a binary as the first element of each hash value. That binary is used to represent if the hash is on the left or the right side of the pair. A nice solution is to sort the pairs before hashing, and decide the position based on the larger value, however limitations of the number range usable in ZoKrates make this infeasible.

Authorizing Balance Updates We still need to ensure the user has authorized this balance update though. As balance updates are emitted as an event, anyone can access them and compute valid merkle paths for any balance in our system. The data is public. This would, for example, allow any user to withdraw any balance. To ensure a user is authorized to update a balance, we need ensure the user controls the private key belonging to the balances user address. This can be achieved by requesting a signature from the user. However, it must be remembered, that this signature must also be verifiable in our ZoKrates program, which is unable to utilize the secp256k1 curve, used for signing Ethereum transaction, efficiently [6]. For that reason the Baby JubJub curve is used in combination with the EdDSA signature scheme, which can be run more efficiently in a ZoKrates program. The user submits a signature containing the current merkle root and the update message. This ensures three things. It proves the user controls the private key belonging to the balance objects address, thereby authorizing the order. We also make sure, the balance update corresponds to the amount signed by the user, ensuring the transition is done correctly. By signing the current merkle root, we make sure, that the signature can't be reused in a replay attack. For instance, the aggregator could decide to store these signatures secretly, and reuse them without the users consent if this was omitted. By checking if the current root is equal to the signed root when verifying the zkSNARK proof, we prevent replay attacks. It is important to note, that different programs are used for deposits/withdraws and trade aggregation. As already mentioned, these programs have a number of checks that ensure the changes in balance correspond to the values specified in the signed update message. These will be explained in the respective sections.

Creating a EdDSA Signature At the time of writing, metamask does not support signing with the EdDSA signature scheme on the Baby JubJub curve. Fortunately, we can derive a Baby JubJub private key from an EcDSA signature, and then use the derived key to sign with the EdDSA signature scheme over the Baby JubJub curve. This signature can then be verified cheaply in a zkSNARK circuit. It must also be mentioned, that we utilize the MiMC hashing function to hash the message, as its efficient to run in a zkSNARK circuit.

explain situation
with hermez

Executing and Reducing On-chain Verification Costs All of these checks are performed as a ZoKrates program. If no checks fail, the proof can now be generated. We have now successfully verified the new balances, and we could use these values to generate the proof, which will then be used to verify everything on-chain. When verifying the ZoKrates program on-chain, each output of the program is part of the proof object, adding an iteration to the proving logic. The amount of outputs the ZoKrates program has, influences the verifications costs. We can reduce this cost by returning a hash of the resulting data, thereby reducing the amount of outputs. Since the aggregator

computed the balances in the first place, and the ZoKrates program only verified the updates, the aggregator can pass that data as part of the verify transaction, but excluded from the ZoKrates proof object. By hashing the data with the SHA256 hashing algorithm in the zkSwap smart-contract, we can ensure that data correctness by comparing it to the hash that is part of the proof object. As a result, the ZoKrates program only returns this hash as an output value, which we call the data hash. While the SHA256 hashing algorithm is inefficient to run in zkSNARK, and its very cheap use in a smart-contract. Since every balance update in an aggregation batch needs to be hashed on-chain, reducing the on-chain cost is more favorable, compared to reducing the complexity of the zkSNARK program.

3.2.3 Deposit

When using the system, a user first has to deposit funds. Since the entire idea of zk-rollup is to move funds to layer-2, the deposit function can be seen as a bridge that connects the mainnet and layer-2. When a user makes a deposit, the funds are represented as a balance object in layer-2, which in turn gives custody to these funds. When moving funds in layer-2, we don't actually move the funds residing in the smart-contract, but update the balance objects to represent the movement and verify that movement for correctness with a zkSNARK proof. Since a balance object gives a user custody of represented funds, it can always be redeemed, moving from layer-2 back to mainnet.

Movement of Funds To move funds to layer-2, a user first needs to send the funds to the zkSwap smart-contract. This is done by calling the deposit function in the zkSwap smart-contract and attaching the funds to the transaction. The deposit function now emits a 'Deposit' event, containing the type of fund (Ether or ERC20), the amount and the address of the user making the deposit. This event notifies the aggregator of the deposit and ensures the user has actually deposited a certain amount of funds. This is the first step of the deposit.

Aggregating Deposits After the funds have been sent to the smart-contract, the user creates a signature containing the type of aggregation (deposit/with), the changes in Ether and token balance, the users address and the current merkle root. This signature is sent to the aggregator as an HTTP request. The aggregator checks the signature of each incoming request and makes sure a matching 'Deposit' event has been emitted. This ensures the user has actually sent funds to the smart-contract. After a number of deposits have been received, the aggregation is started. The aggregator now generates a 'BalanceMovementObject' for each deposit, containing the old balance, the new balance, the merkle path and the signature. This is passed to the 'Process-BalanceMovement' ZoKrates program, along with the current merkle root. As explained in S. 3.2.2, the inclusion proof is now performed on the old

Maybe remove this?

balance. If the old balance is included in the merkle tree, the signature is checked, along with the change of balance. The signed amount should equal the added amount in the new balance, the nonce must be incremented and the address the same. If these checks pass, we calculate the new merkle root, by rehashing the new balance with the merkle path. We do this for each ‘BalanceMovementObject’, and hash the new balances, as explained in S. 10, along with the old merkle root and the new merkle root, to reduce the on chain verification costs. This results in the data hash.

Verifying Deposits On-chain Once the ZoKrates program has run successfully, the proof can be generated, which is used for verification in the zkSwap smart-contract. The aggregator calls the ‘verifyBalanceMovement’ function in the zkSwap smart-contract and attached the proof, along with the new balances and the old and new merkle root to the transaction. As a first step, the balances and roots are hashed, and the result of the hash compared to the output field in the ZoKrates proof object. If these hashes match, we can be assured, the aggregator has attached the data that has been checked by the ZoKrates program. Next, we check if the old root, matches the current root stored in the zkSwap smart-contract. This ensures that a generated proof can’t be reused in replay attacks. As a last check, the ZoKrates proof object is checked with the verifier smart-contract deployed for this purpose. If this is also successful, we have proven, that the aggregator has processed the deposits correctly. We now iteratively emit the new balance objects with the ‘BalanceUpdate’ event, and update the merkle root in the smart-contract. The deposits have now been processed and show up as balance for the users.

3.2.4 Aggregated Withdraws

The aggregated withdraws largely follow the logic of the deposits, so only the core differences will be explained here. Instead of sending funds to the zk-Swap smart-contract, we are requesting them. Since the user already has a balance in the system, we don’t need to notify the aggregator about the amount a user wants to withdraw, which in turn means we don’t need an on-chain transaction to trigger the withdraw. A user creates a signature of its address, the current merkle root, type of funds and the amount to be withdrawn, and sends it to the aggregator as an HTTP request. Once the aggregation starts, the aggregator checks the users signature, and ensures that the users balance covers the withdraw. Just like with deposits, a ‘BalanceMovementObject’ is created, the type being set to withdraw. The withdraws are verified along with the deposits in the same ZoKrates program. This results in only one on-chain verification, which reduces verification costs. The ‘ProcessBalanceMovement’ checks signature, the balances and if the balance update corresponds to the amount signed by the user. On top of hashing the new balances, a withdraw object is also hashed, containing the type of

funds and the amount. When verifying withdraws, along with the deposits, the withdraw objects will be used to send the funds from the smart-contract to the users. The new balances are emitted and the root updated.

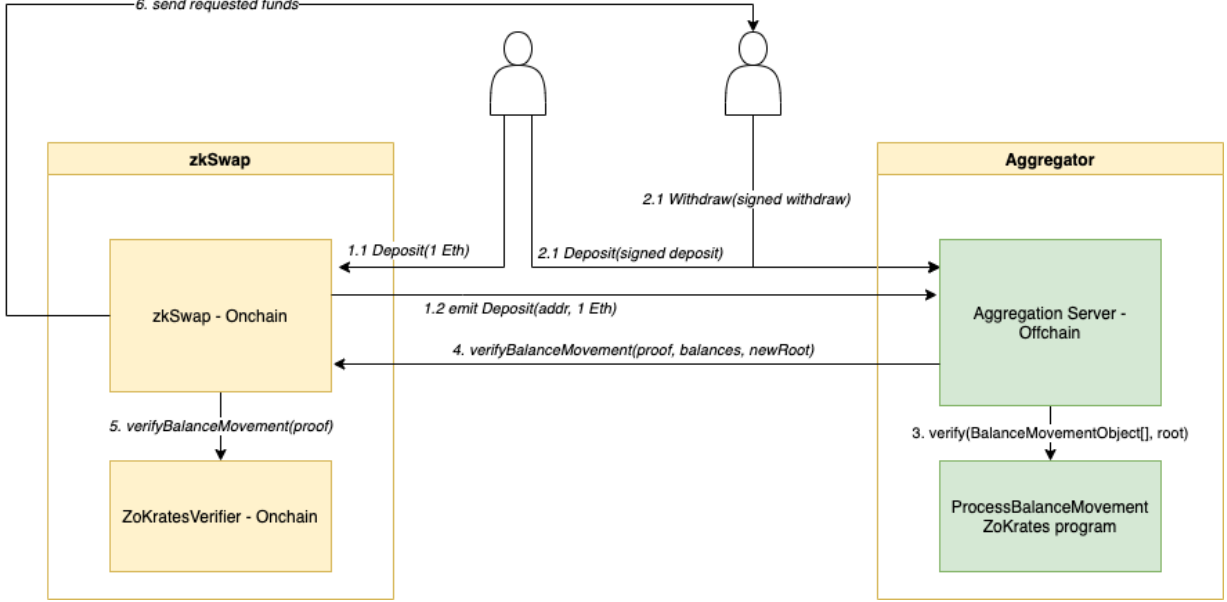


Figure 3: Interaction diagram of aggregated deposits and withdraws

3.2.5 Instant Withdraws

A user also has the option to withdraw instantly, without being dependant on the aggregator. This ensures a user can always withdraw funds, even when the aggregator is failing or offline. Instead of sending the withdraw request to the aggregator, the withdraw is processed completely on-chain. The user attaches its balance object, along with the corresponding merkle path and the withdraw amount and fund type (Ether/ERC20) to the transaction. As a first step, the merkle inclusion proof is performed. The balance object is hashed, sequentially with the merkle path. The resulting hash now equals the merkle root stored in the zkSwap smart-contract if the correct balance object and merkle path have been submitted. It is checked if the balance can cover the withdraw, if that's the case the nonce is incremented, the new balance is calculated, and the new balance object hashed again. The new root is now computed by hashing with the merkle path, and updated in the smart-contract. The funds are now sent to the user and the new balance is emitted. It must be reiterated, that this is done completely on-chain and doesn't require the aggregator to be online. However, the gas costs of this transaction are significant, as hashing with the MiMC hashing algorithm is expensive in a smart-contract.

Authorizing Instant Withdraws This however, is an incomplete explanation, as we're not checking if a user is permitted to withdraw funds. As balance objects are emitted as an event, anyone can access them and compute valid merkle paths for any balance. This would allow any user to withdraw any balance. To ensure a user is permitted to update a balance object, we need ensure the user controls the private key belonging to the balance objects user address. Fortunately, we can ensure this by accessing the sender in transaction object. The Ethereum blockchain ensures a user is allowed to make a transaction by requiring the transaction to be signed with the private key of the senders address. If that signature is valid, it is proven that the user has access to the addresses private key and the transaction can be executed. Because of this, the transactions object sender can be trusted to be in control of the corresponding private key. Instead of passing the users address as part of the balance object, the smart-contract uses the sender of the transaction object. This suffices as a security check.

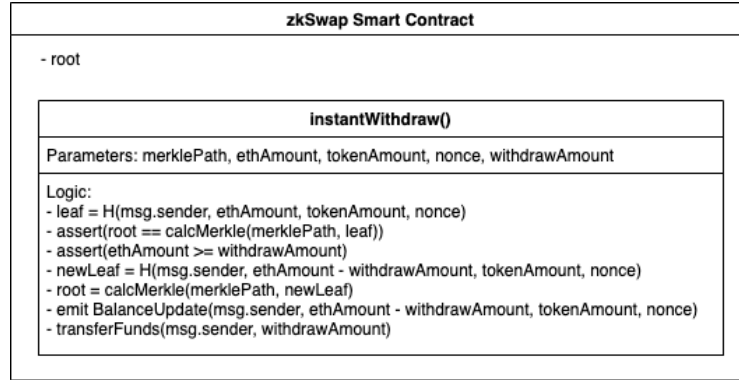


Figure 4: Pseudocode of instant withdraw steps

3.2.6 Aggregating Trades

Before explaining the life-cycle of a trade aggregation batch, it makes sense to understand the mechanism that ensures the correct price of trades in an aggregation batch. After, we will go through the entire life-cycle of an aggregation batch, starting with a user adding a trade.

Ensuring Correct Pricing The price between assets is constantly changing. At the same time, trades are being collected for aggregation. This results in a delay between an user sending a trade order and the actual trade execution, during which the price of an asset can change. On top of that, network congestion on the Ethereum blockchain can cause further delays in the execution. A mechanism is needed to define a 'worst-case' price, that is defined before users add orders to the aggregation. Once the aggregation is complete, a user can be sure to having paid no worse then the 'worst-case' price.

Another thing to consider is the bid-ask spread that exists in a trading pair. A spread is the difference between the current bid and ask price for an asset, where the bid always has to be a lower price. Intuitively, this makes sense, the spread should at least equal the cost of converting from one asset to the other. There are a number of other factors that influence the bid-ask spread for a Uniswap trading pair. In this context however, it is sufficient to know that a spread is expected in any trading pair. This complicates the mechanism to ensure a worst-case price.

Buy and sell orders are off-set internally once the aggregation starts, which results in the ‘net trade’. Since we don’t know what orders will be received in an aggregation batch, we’re unable to predict if the ‘net-trade’ will be a buy or sell order. Since we have a bid-ask spread, and we can not predict which direction our net trade will be, we need to define a price range that at least equals the current bid-ask spread. This would suffice to ensure a worst-case price for a net trade in either direction if executed immediatly. As the aggregation is also adding a delay between defining the price range and executing the trade, the price range should be larger then the spread. For this reason the zkSwap smart-contract defines a minSell and maxBuy price, defining that range. If the price on Uniswap has moved out of that range, while the aggregation was in progress, the trade won’t be executed and the aggregation canceled. This can be formalized in the following way:

$$\forall A_o \in A : x_s \leq x_e \leq x_b$$

where:

A is the current aggregation batch

A_o a trade order

x_e is the effective price

x_s is the minSell price

x_b is the maxBuy price

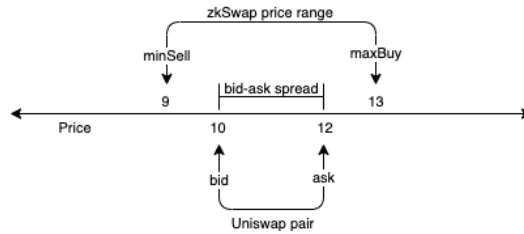


Figure 5: Bid-ask spread and zkSwap price range

While this method ensures a ‘worst-case’ price for a trade, at the same time a maximum price is defined with it. Since we’re matching buy and sell

orders in one aggregation, there is no way around this. Once the aggregation is completed and verified on-chain, the new minSell and maxBuy prices are set, based on queried Uniswap prices, which are valid for the next aggregation batch.

Adding an Trade Order To make a trade, a user must create an trade object and sign it with its private key. The trade object consists of five fields that are needed to define the trade, the tradeDirection, deltaEth, deltaToken and the users address and current merkle root. Since ZoKrates only uses unsigned integers, we need the tradeDirection to calculate the new balance. Once signed, the trade object is sent to the aggregator as an HTTP request. As a first check, the aggregator checks if the signature is valid. This ensures, that the trade object was created by the someone in control of the addresses private key, thereby authorizing the trade order. The aggregator now queries the users balance from its merkle tree, and checks if the merkle root in the trade object is equal to the merkle root set in the zkSwap smart-contract. This ensures the signed trade object can't be reused in replay attacks. The aggregator also checks if the users balance can cover the trade, making sure enough balance has been deposited. A last thing to consider is ensuring the correct price of a trade. The aggregator checks if the implied price of the trade matches the 'worst-case' price stored in the zkSwap smart-contract. If all of these checks pass, the order is added to the trade pool, where it resides until the aggregation starts. It must be noted, that these checks are technically not needed to ensure the correctness of the aggregation, as the ZoKrates program performs the same checks. They are however needed, to prevent the aggregator from processing invalid trades, which would cause the ZoKrates program to exit in an error state, preventing the entire aggregation. A trade is invalid, if it fails any of the checks described in this paragraph.

Executing Trade and Calculating New Balances At some point the trade aggregation is started. This could be triggered by a set blocknumber, the number of trade orders that have been received or any other useful condition defined by the aggregator. When aggregation is started, the first step is to calculate the 'net trade'. Since our system aggregates buy and sell orders, we can offset those internally. By doing this, we're able to reduce the entire aggregation to one Uniswap trade, which saves gas. At the same time, we're saving on the 0.3% liquidity provider fee, which is charged based on a trades volume. The net trade is the result of off-setting all trades in aggregation, buy or sell order, which results one side to equal zero. This trade is now sent as an on-chain transaction to the 'PairProxy' contract, where the trade is now executed with Uniswap. The PairProxy contract is explained in detail in S. 3.2.7.

The aggregator waits for the PairProxy smart-contract to emit the 'Trade-Complete' event, which will fire once the trade has been executed, containing the amount of assets acquired in the Uniswap trade. The amount received must

at least imply the worst-case price, defined by the zkSwap smart-contract. In most situations, the implied price (effective price from here) will be better than the worst-case price. Based on the effective price, the users post-trade balances are calculated. For each trade, a ‘BalanceUpdateObject’ is created, containing the old balance, the new balance, the merkle path and the signed trade object. The merkle paths for each ‘BalanceUpdateObject’ are created as explained in S. 3.2.2. Now the ‘ProcessTrades’ ZoKrates program is called, along with the ‘BalanceUpdateObjects’, the current merkle root and the worst-case price.

Checking Pricing in ZoKrates We want to make sure that each trade has the same price, no matter if its a buy or sell order. It is also important that this price is no worse than the worst-case price, defined in the zkSwap smart-contract. We iterate through the ‘BalanceUpdateObjects’, checking if each trade has the same price, and making sure it’s greater or equal to the worst-case price. While doing this, we also calculate the ‘net-trade’, which will represent the flow of funds between the zkSwap smart-contract and the aggregator. After this has completed, we are assured that each user is receiving a equal rate, at least matching the worst-case price², and we have calculated the ‘net-trade’, which will be important when finalizing the aggregation.

Verifying Balances and Authorization in ZoKrates To ensure the correct aggregation of these trades, we still need to ensure the submitted old balances are part of the merkle tree and that the user has authorized the trade. While the aggregator has checked this already, it must be remembered, that the aggregator is an untrusted party. We need to be able to verify the correct execution of these checks on-chain, which can be achieved with zkSNARK. To ensure this, we largely follow the steps described in S. 3.2.2. We iterate through the ‘BalanceUpdateObjects’ sequentially, checking if the merkle root can be recreated. If that’s the case, we check if the signature is valid, and if the balance change matches the amounts specified in the trade object. Since the price has been checked already, we’re only checking the amounts here. Now we compute the new merkle root, based on the new balance. This root is then used to verify the balance of the next ‘BalanceUpdateObject’, details of this are explained in S. 3.2.2. The last merkle root computed is the new merkle root, representing the entire merkle tree with the updated balances.

Reducing On-chain Verification Costs in ZoKrates We have now successfully verified the new balances, and we could use these values to generate the proof, which will then be used to verify everything on-chain. As explained in S. 10 we can still reduce the gas needed for verifying the aggregation batch on-chain, by hashing the results, thereby removing them from the zkSNARK

²The worst-case price will be compared to the one stored in the zkSwap smart-contract at a later stage, enforcing it for the entire aggregation.

proof. As the last step of the ZoKrates program, we hash all new balances, the old and new merkle root, the net trade and the worst-case price. The resulting hash, called the data hash, is the only output of the ZoKrates program.

ZoKrates Program
Parameters: oldBalances, newBalances, merklePath, proofFlags, root, priceEth, priceToken
<ul style="list-style-type: none"> - check oldBalances by hashing tree and comparing root - check if newBalances imply correct price - calculate effective net trade (PairProxy <-> zkSwap) - compute new root by hashing tree with newBalances - compute dataHash to commit verified state - return dataHash

Explain assumptions that can be made from proof in background, hashing as algo blaaa

Figure 6: ZoKrates program checks

Generating Proof and Verifying At this point the aggregator can start the proof generation of the ZoKrates program. This proof object is needed to verify the correct execution of our ZoKrates program as an on-chain transaction in the zkSwap smart-contract and includes, among other things, our data hash. To verify everything on-chain, and thereby updating balances of all balances involved in the aggregation, the proof object is passed, along with the new balances, the new merkle root and the net trade and sent to the PairProxy smart-contract. The ‘PairProxy’ smart-contract receives the transaction, adds the funds previously traded with Uniswap to the transaction and forwards it to the ‘verifyTrades’ function in the zkSwap smart-contract.

Verifying the ZoKrates Proof The first thing checked in the zkSwap contract when receiving a trade aggregation batch, is the ZoKrates proof object. The verifier smart-contract is generated along with the the ZoKrates program, and can be used to verify the correct execution of that program using the proof object it generates. The verifier is called, along with the proof object passed as parameter. If the verifier return true, we have proven that our data hash was computed by running the ‘ProcessTrades’ ZoKrates program, which in turn was used to generate the verifier. The remaining steps of the trade aggregation life-cycle happen in the zkSwap smart-contract, purely on-chain.

Recreating the DataHash and Ensuring Correct Price As a next check, we need to ensure that the aggregator has attatched the same data verified by the ZoKrates proof generation. This can be done by recreating the data hash. Just like the merkle root, this hash commits a certain state, which we can verify at a later stage. By using the properties of zkSNARK, we’re able to create this commitment off-chain, saving gas. We hash the balances, along with the worst-case price, the new and old merkle root and the net

trade with the SHA256 hashing algorithm. The old merkle root and worst-case price, however are not parameters attached to the transaction. Since these values are stored in the zkSwap smart-contract, we use these values. This ensured the correct values were used throughout the entire life-cycle of the aggregation. The aggregator could use an incorrect worst-case price and old merkle root, along with valid merkle paths. By having these values part of the data hash and querying them from the smart-contract, we can ensure the aggregator stays truthful and provides correct data. Failing to recreate the data hash will result in the aggregation being canceled.

Receiving Fund and Refunding Aggregator While the balances of users are updated in layer-2, funds between the aggregator and zkSwap smart-contract must still flow as an on-chain transaction. Since the aggregator has executed the ‘net trade’ and updated the balances accordingly, these funds need to be exchanged in order for the zkSwap contract to stay solvent³ and for the aggregator to be refunded for the executed Uniswap trade. Since the net trade has been passed as a parameter and is verified by the dataHash, we check if the funds passed as part of this transaction match the amount of the net trade. If the amounts match, aggregator is refunded the amount spent in the Uniswap trade.

Updating Root and Emitting Balances The root is updated in the smart-contract, the worst-case prices are updated by querying Uniswap and the new balances are emitted via the ‘BalanceUpdate’ event, updating the state for all involved users. The lifecycle of a trade aggregation is now complete, and the next batch starts.

3.2.7 PairProxy Smart Contract

Before explaining the functionalities of this smart-contract, it is important to understand why it is required for the system to function. There are two reasons, a quirk in the way Ethereum handles return values, and the result of dealing with changing price data. When performing a trade on Uniswap, a user is asked to define a slippage⁴ for the trade. Since network congestion and the current gas price influence when a transaction is executed, it’s a necessary mechanism for ensuring users can set a ‘worst-case’ price. For this reason, when sending a transaction to the Uniswap trade function, the minAmountReceived parameter must be passed, which we provide by using our ‘worst-case’ price, explained in a previous section. When calling the trade function, the actual amount received is returned as the functions return value.

³The zkSwap contract is solvent if its always able to cover the withdraw of all balances. The zkSwap contract should always be solvent.

⁴Slippage is the difference of the expected and executed price of a trade

Since this amount might be larger than the amount passed as `minAmountReceived`, we need it to calculate the post-trade balances⁵.

However, a quirk in Ethereum's way of handling return values makes this more difficult. A smart-contract's function return value can only be accessed, when called by another smart-contract function. If calling a function as a normal transaction, as the aggregator does, instead of receiving the return value of the function, we receive the transaction receipt, which doesn't contain the return value. For this reason, we need the `PairProxy` smart-contract, which receives transactions, forwards them to the respective smart-contract, emitting the return value as an event, which can be consumed by the transactor.

The `PairProxy` smart-contract is used for forwarding transactions to the `Uniswap` or the `zkSwap` contracts. After the aggregator has calculated the 'net trade', it calls the trade function in the `PairProxy` contract, passing the calculated trade parameters. The `PairProxy` contract now calls `Uniswap`'s trade function, receiving funds and the amount as a return value. As it has access to the return value, it emits the 'TradeComplete' event, containing the amount received in the trade. As it would be inefficient to send the funds back to the aggregator, they reside in the smart-contract. Since the aggregator is set as the owner of the contract, the funds are stored securely.

When verifying the aggregated trades in the `zkSwap` smart-contract, the transactions are forwarded by the `PairProxy` again. Since the funds previously traded still reside in the smart-contract, they are attached to the transaction when forwarded to the `zkSwap` smart-contract.

3.2.8 Client Frontend

The frontend allows the user to interact with the system, calling the functions, while providing necessary data in the background. The frontend also listens for 'BalanceUpdate' events and keeps the merkle tree in sync locally. This allows the client to access the merkle tree in order to provide the merkle path for a transaction for example, without relying on an external system to provide this data. In its current design, the frontend could be hosted as a static file in IPFS [5], not relying on any server to facilitate withdrawals of user funds, which closely follows Ethereum's unstoppable applications ethos. Running this with a large merkle tree becomes unfeasible quickly though, so a hybrid approach can be envisioned. A server is used to provide the user with requested data from the merkle tree. If the server is offline or provides incorrect data, the client can sync merkle tree itself. While this would put computational strain on the client, it ensures that a user is always able to withdraw funds, no matter what entities are offline or have turned malicious.

Deposits and Withdraws In order to deposit and withdraw funds, the user needs to specify a number of parameters, that are needed to execute

⁵The trade also throws an error, when the `minAmountReceived` amount can't be fulfilled. In this case the aggregator cancels the aggregation

the transaction. First of all the merkle path is needed, which the client can generate by querying its local instance of the merkle tree. The balance object can also be provided by the merkle tree. A form in the frontend is used to define the amounts wishing to be deposited/withdrawn, which will gather the necessary parameters and add them to a Ethereum transaction. Metamask or any other browser compatible wallet will open, summarizing the transaction, which a user can now sign, bringing it on chain. Once the ‘BalanceUpdate’ event is fired, the frontend will update the balance in its merkle tree.

Adding a Trade When adding a trade a user defines the direction of the trade and the amount wishing to be traded. The trade form will display a minimal amount received, which is calculated based on the worst-case price for either trade direction. Since this is an off-chain transaction, when sending the order a user is asked to sign the order and the current balance root with its addresses private key, explained in detail in S. [?]. The order is now sent to the aggregator as an HTTP request.

Displaying Account Data The frontend also displays basic account data, which makes usage of the system easier. This includes the accounts current balances, as well as the address. Redux is used in the background to keep the data in sync.

3.3 Limitations of Current Implementation

The final implementation of this work does not include all attributes mentioned in the previous sections.

Signatures As described in S. [?], the authorization of an order or deposit entirely relies on a user signing the trade order and merkle root. This signature needs to be checked in a ZoKrates program, which limits us to use the EdDSA scheme, in combination with the BN128 curve. Hermez [?], a zk-rollup based asset transfer system, has solved this by creating a Baby JubJub[4] private key from a signed EcDSA message, which can be requested by Metamask. The generated private key can then be used to sign in EdDSA on the BN128 curve. I don’t have a written source for this, but talked to their team members, who explained how they do this. Since their system is running on mainnet now, it can be assumed to work. In the systems current form, signatures are not checked at all.

Updating Balances According to Effective Price After the aggregator has executed the net trade on Uniswap, the new balances are calculated based on the worst-case price instead of the effective price the aggregator has paid. Currently, there is no mechanism in place that can ensure this. The aggregator could always claim the worst possible price has been paid (depending

on net trade direction), while keeping the difference for itself. This will be addressed in the open problems section.

Hashing Function In its current form, the system doesn't utilize the MiMC hashing yet. All hashing is currently done with SHA256, which limits the number of trades or deposits/withdraws that can realistically be part of a batch. The ZoKrates programs have been updated to utilize MiMC, however I was unable to create matching hashes in the smart-contract.

Aggregating Deposits and Withdraws Since the MiMC hashes are not implemented yet, the aggregated withdraws aren't ether. Using SHA256 in a smart-contract is cheap, so executing the inclusion proofs on-chain is viable to a certain extent. The ZoKrates programs have been finalized, and the changes in the aggregator are also rather small, so this could be implemented without too much work, once the smart-contract MiMC implementation produces matching hashes. So in this form, deposits and withdraws are done on-chain, pretty much the way the instant withdraw works, but using SHA256 to hash the merkle tree.

4 Results

In this section we will look at a number of metrics that are useful for judging the systems performance. In zkSNARK enabled systems, the results must always be considered out of two different point of views. For one, the changes in gas usage are important. After all, this system is built to reduce gas consumption per trade. Another thing to consider, is the performance of the zkSNARK steps that are necessary to execute and verify a circuit. As zkSNARKs rely on complex cryptographic primitives, the generation of proofs can take a long time, even on powerful hardware. We will start by looking at the gas usage results first, and then look at a number of metrics for the zkSNARK circuits.

Notarize execution
maybe the correct
word?

4.1 Gas Cost

In this system, we have four different operations that require gas to be executed. We will now look at these operations, presenting the measured results. The following three charts are scaled logarithmically on the x-axis. The logarithmic scale was chosen, as these operations have a large overhead (fixed cost) and a proportionally small amount of variable cost. This results in the cost per trade to reduce significantly in the beginning, which can be visualized best on a logarithmic x-axis scale.

4.1.1 Trade Aggragation

To break down the gas cost of a trade aggregation batch, we must first differentiate between fixed and variable gas cost that need to be paid per batch and trade. For one, the gas for the net trade, executed on Uniswap, must be paid. This amount varies, depending on the direction of the net trade, 142k when trading from Ether and 167k gas when trading from an ERC20 token.

Another fixed cost to consider is the gas for verifying the zkSNARK proof, along with handling the refund payment of the aggregator and the checks defined in S. 3.2.6. Executing these costs 342k gas per aggregation batch. The combined fixed amount of gas per aggregation batch is 484k/ 509k gas, depending on the net trade direction. For each trade in a batch, we must pay 6619 gas, which is used for recreating the data hash, as well as emitting the BalanceUpdate event. When using these numbers, we get the following cost per trade, depending on the batch size. In this diagram, we're using the more expensive net trade (ERC20 to Ether) to calculate the results, which results in the maximum cost per trade for the corresponding batch size. As the difference is small, the difference in gas per trade converges quickly. The theoretical maximum batch size is 1811, which is where Ethereum's block gas limit is reached.

To compare the results to a normal Uniswap trade, we define a break even price, which is equal to the cost of a Uniswap trade. Our system makes sense economically once our gas per trade cost is lower than the break even point. We will use 142k gas as our break even point, which is the best case for a Uniswap trade. The numbers found in this diagram do not contain any gas cost required for making a deposit or withdraw.

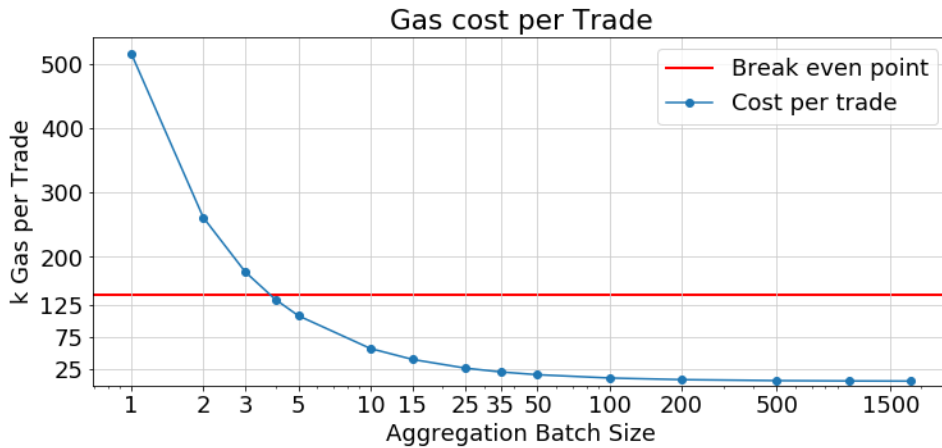


Figure 7: Gas cost per trade and breakeven point

4.1.2 Deposits and Withdraws

Before a user is able to trade, funds must be deposited into the system. Presenting these results is a bit more difficult compared to the trade aggregation results for two reasons. For one, the deposits and withdraws are aggregated as one aggregation batch. Since the gas costs for a deposit and withdraw are different, and the number of deposits and withdraws included in a batch is not predicatable, the cost per deposit/withdraw depends on the proportion of deposits and withdraws in a batch. On top of that, the gas cost of an deposit/withdraw also depends on the asset. Ether deposits/withdraws are cheaper than ERC20, which is a result of how tokens are represented on the Ethereum blockchain. For this reason we will present three quartiles for deposits and withdraws, that represent the share of an asset in the batch. For example, as seen in F. 8, ‘25% Eth’ represents the gas cost per deposit if 25% of deposits in that batch are Ether deposits. While the numbers are a bit inaccurate for smaller batch sizes, it seems like the best approach to present the results overall.

Deposit Aggregation As with the trade aggregation, there is a fixed and a variable gas cost required per batch. For each deposit aggregation we have 312k gas as a fixed cost. This involves all checks and verifications explained in S. 3.2.3. The variable gas cost depends if an Ether or an ERC20 token is deposit. Depositing an ERC20 token requires significantly more gas then sending Ether, as multiple smart-contract interactions are necessary. An Ether deposit adds 23k gas, an ERC20 deposit 116k gas. The maximum batch size is chosen based on the worst-case proportions, in this case only ERC20 deposits and the number of deposits we can include before Ethereum block gas limit is reached. For deposits that a maximum batch size of 105.

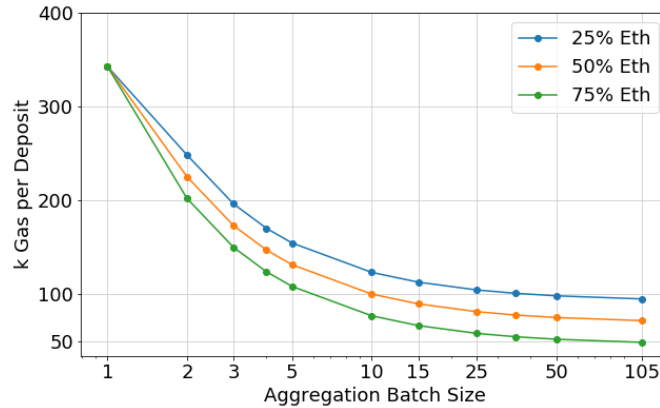


Figure 8: Gas cost per deposit assuming different share of Ether deposits

Withdraw Aggregation The fixed costs of the withdraws is equal to the amount specified in the deposit aggregation, as they are being verified in the same batch. As with the deposits, the variable withdraw cost is different, depending if Ether or an ERC20 token is withdrawn. The maximum batch size is chosen based on the worst-case propotions, in this case only ERC20 withdraws and the number of deposits we can include before Ethereum block gas limit is reached. For deposits thats a maximum batch size of 186.

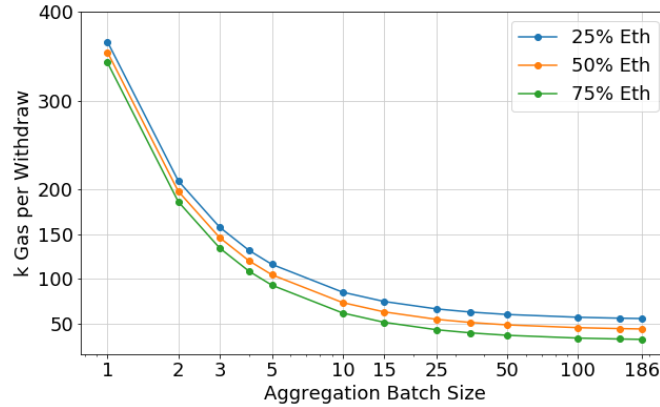


Figure 9: Gas cost per withdraws assuming different share of Ether withdraws in batch

Combining Deposit and Withdraw Gas Cost Modeling the combined gas costs of deposits and withdraws is omitted in the work, as there are too many assumptions that need to be made. As mentioned before, the proportion of Ether and ERC20 operations, as well as the proportion of deposits and withdraws influence the results. For the deposits and withdraws a valid approach was taken to model the potential gas cost, depending on the proportional share of funds. Combining these values, defining the proportional share of deposits and withdraws in an aggregation batch wouldn't yield representative results, as there are a number of valid combinations that would need to be considered. The diagrams presented above give a clear indication of the potential cost, which suffices for this work.

Instant Withdraws The cost of instant withdraws is also worth considering. Since we're not batching instant withdraws, there is only a fixed cost per withdraw that needs to be paid. Since this hasn't been implemented at the time of writing, a rough estimate of the gas costs can only be provided. To update a balance in a merkle tree with a depth of 16, we need to hash a total of 34 times. 32 times for the merkle inclusion proof and update, twice for hashing the old and new balance. Computing as MiMC hash currently

costs 94k gas, which would bring the cost to around 3.2m gas per instant withdraw.

4.2 zkSNARK Circuit Metrics

Another aspect to consider is the performance of the zkSNARK circuits. The benchmarks for the zkSNARK circuits were performed on a Google Cloud Platform C2 instance, with 60 vCores (3.1GHz base and 3.8GHz turbo) and 240Gb of memory. This instance was chosen because of the large amount of memory and the fast clock speed. The number of cores doesn't impact the benchmarking results, as the zkSNARK steps can't be parallelised at the time of writing.

4.2.1 Execution Time

The first obvious metric to consider is execution times of the different steps required to utilize our circuits.

Compilation and Setup Before we can generate any zkSNARK proofs, we have to compile our circuits and run the setup. These two steps only need to be run once per circuit, so they're not significant for the viability of this system. However I have the numbers, and it would feel incomplete to not present them. These are the results, for the trade and deposit/withdraw circuit.

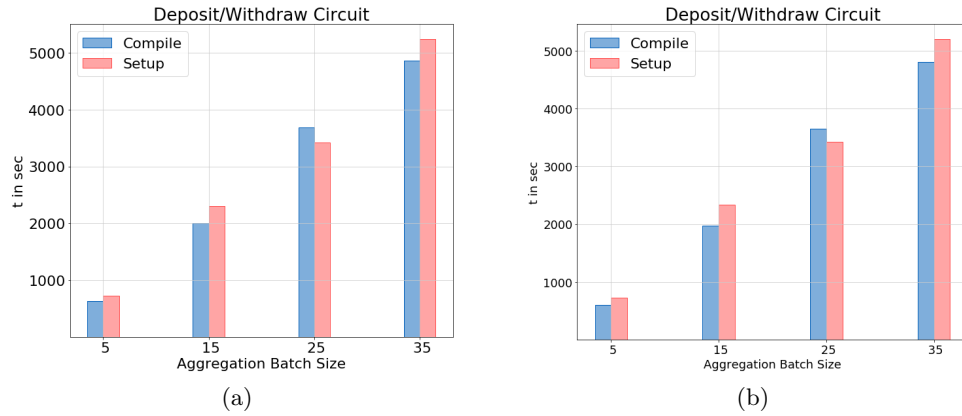


Figure 10: Compilation and setup execution times

Witness Computations and Proof Generation For each aggregation batch we need to first run the witness computation, after which the proof generation can be run. These two steps need to be run for every aggregation batch, so the performance is a indicator for the viability of this system. It decides how long the aggregation of a batch takes, which impacts the practical application of this system.

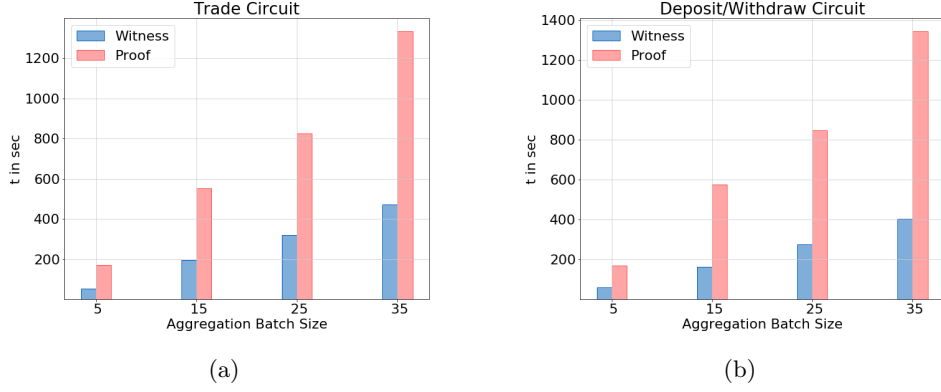


Figure 11: Witness computation and proof generation

4.2.2 Memory Usage

Only looking at the execution times gives us an idea how many operation can be batched. It tells us nothing about the hardware requirements needed for working with circuits of this size. One thing to look at, is the memory used in the different steps. In general, the memory consumption of these processes is high, which is why a server instance with such a large amount of memory was chosen.

Compilation and Setup When measuring the compilation memory consumption, we get a confusing picture. The results don't really make sense, as smaller circuits sometimes require more memory as smaller ones. However, I repeated this measurement on different machines and operating systems, always receiving inconclusive results, similar to these. I watched the compilation on the server with `htop`, and observed the same amount of memory that the memory usage script was detecting. The script uses the command line tool `'ps'` to take these measurements, which measures reserved memory by a process. Alternatively, a profiler could be used to measure the actual memory usage. This would impact the performance of the application severely though. As these steps only have to be executed once, they are not a meaningful metric.

Witness Computation and Proof Generation The memory required for running the witness computation and proof generation is an important metric and dictates the hardware needed for the aggregation process. We need to run these steps for every aggregation batch, so hardware capable of handling the memory requirements must be available.

4.2.3 Constraints

Looking at the results, we see that the execution times increase linearly with the batch size. The same pretty much goes for the memory consumption of

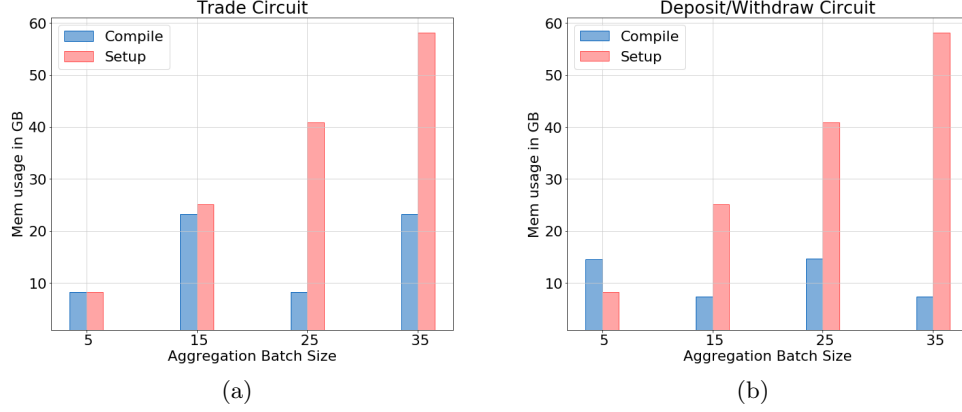


Figure 12: Compilation and setup memory consumption

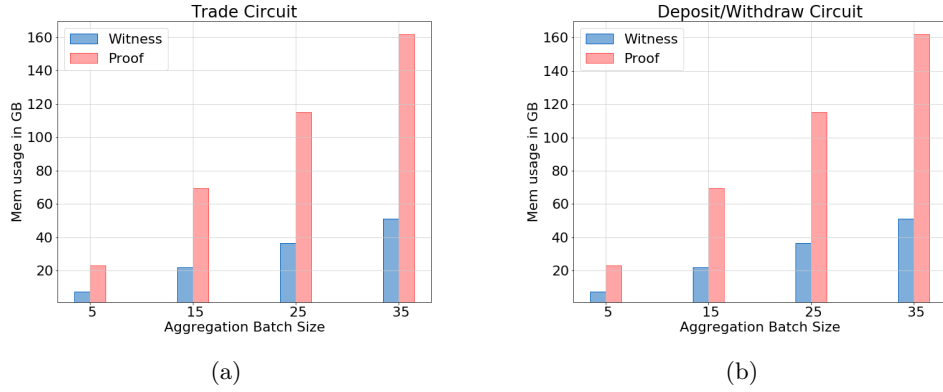


Figure 13: Witness computation and proof generation memory consumption

our circuits. As a general rule, the complexity of a zkSNARK circuit is defined by amount of constraints the circuit is made of. Each additional element in the batch adds a certain number of constraints to the circuit. Looking at our circuits, we get the following constraint counts for different batch sizes.

Origin of Constraints Both circuits can be broken down into three different main segments, that add a certain number of constraints. 1) We need to run the inclusion proof and update the merkle tree. 2) We check the signature and if the balance update follows the signed amounts. 3) We need to compute the data hash. For each of these operations, we get constraint numbers that are added per additional batch element. These numbers were measured by compiling the segments separately and checking the constraint count. Comparing these to the total constraint values, we realize that they are higher. This can be explained by the ZoKrates optimizer, which runs a number of optimizations during compilation. As we can see, these values are very similar in both circuits, which is why they have comparable performance.

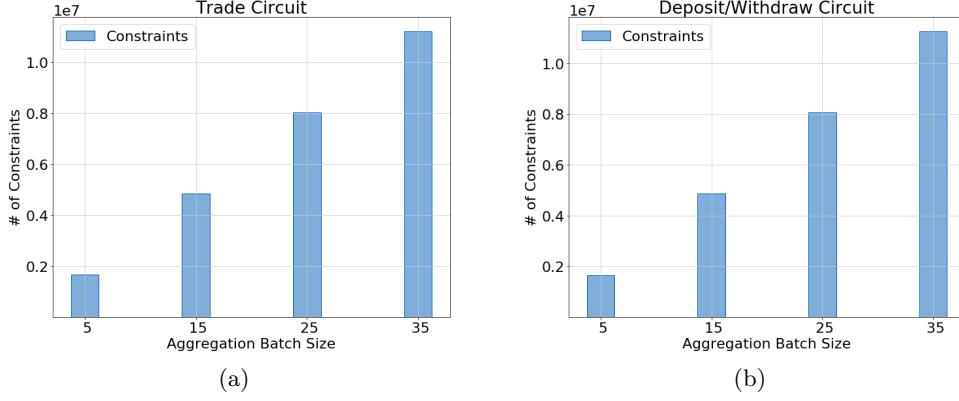


Figure 14: Constraint count for the circuits in different batch sizes

	Fixed Cost:	Variable Cost:
Trade Circuit:		
Merkle Tree	1	179781
Verify sig and balance update	1175	25675
Data hash	182254	184806
Deposit/Withdraw Circuit:		
Merkle Tree	1	179781
Verify sig and balance update	1	28154
Data hash	55970	184806

Hashing and Constraints The MiMC hashing algorithm was used for hashing the merkle tree, as it's more efficient to use in zkSNARK circuits. The most common hashing operation used in the system is the pair hashing of the merkle tree. Every balance update requires 34 pair hashes in total, 1 for hashing the old balance, 16 for the merkle inclusion proof, 1 for hashing the new balance and 16 for updating the merkle tree. We must also remember, that the pair elements need to be sorted according to their position (left, right), which doubles the constraints in a zkSNARK circuit. On the other hand, we also need to hash the balances in the zkSwap smart-contract for recreating the data hash. In Solidity the sha256 hashing algorithm is a lot cheaper than MiMC. Since we have to recreate the data hash for every batch we want to verify on-chain, the data hash is computed with the SHA256 hashing algorithm.

Constraints Processed per Second As last metric we want to take a look at, is constraints processed per second in the witness computation and proof generation step. We can calculate these values by dividing the execution time by the number of constraints. At the time of writing, these steps are not parallelizable and only run on one CPU core. The Loopring protocol claims

Hashing Op	Constraints	Gas Usage
MiMC pair	2642	94052
MiMC pair sorted	5285	94052
SHA256 pair	56227	1722
SHA256 pair sorted	112453	1722

batch_size	Witness constraints / sec	Proof constraints / sec
5	27604	9685
15	29615	8417
25	29088	9612
35	27797	8382
Average	28526	9024

to have parallelized the libsnark library, which we will look at in S. XX. For this reason we are introducing this metric, as we can compare the outcomes and the potential speed up of parrallelizing. On top of that, this metric can also be helpful to test the performance of the circuits on a CPU with higher clock speed.

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