An Empirical Study of Cross-chain Arbitrage in Decentralized Exchanges

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***Abstract*—Blockchain interoperability refers to the ability of blockchains to share information with each other. Decentralized Exchanges (DEXs) are peer-to-peer marketplaces where traders can exchange cryptocurrencies. Several studies have focused on arbitrage analysis within a single blockchain, typically in Ethereum. Recently, we have seen a growing interest in cross-chain technologies to create a more interconnected blockchain network. We present a framework to study cross-chain arbitrage in DEXs. We use this framework to analyze cross-chain arbitrages between two popular DEXs, PancakeSwap and QuickSwap, within a time frame of a month. While PancakeSwap is implemented on a blockchain named BNB Chain, QuickSwap is implemented on a different blockchain named Polygon. The approach of this work is to study the cross-chain arbitrage through an empirical study. We refer to the number of arbitrages, their revenue as well as to their duration. This work lays the basis for understanding cross-chain arbitrage and its potential impact on the blockchain technology.**

I. Introduction

Decentralized Finance (DeFi) [1], [2] is an emerging technology for various financial services that run as smart contracts, often implemented over the Ethereum blockchain network [3]. The DeFi market size was estimated to be over 180 billion USD in late 2021 and 63.1 billion USD in November 2023. Typical DeFi applications include blockchain-based lending: The ability to lend and borrow cryptocurrencies in exchange for interest [4] as well as insurance services. A primary DeFi application is decentralized exchanges (DEXs) that allow the exchange of cryptocurrencies as non-centralized marketplaces connecting cryptocurrency traders.

As the popularity and usage of blockchain increased, so did the challenges and limitations. Some of the most common challenges are scalability, decentralization, and security. The mutual dependency is known as the blockchain trilemma as often the improvement of one compromises others. Numerous projects have implemented various solutions to address these issues, forming their own blockchains as indicated in Table I. Within this table, many blockchains, including Polygon and BNB Chain, are EVM (Ethereum Virtual Machine) compatible and can run smart contracts. Traditionally, such blockchains are independent without the mutual ability to communicate.

Arbitrage refers to the simultaneous purchase and sale of the same asset in different markets in order to profit from differences in the asset price. It exploits variations in the price of identical assets in different markets. DEXs have an inherent potential for arbitrage as several of them refer to a similar set of major cryptocurrencies with dynamic exchange rates influenced by the liquidity of each cryptocurrency. A range of past works study arbitrages in DEXs implemented over Ethereum as a single blockchain [5],[6],[7].

Recently, several methods for facilitating communication between blockchains have been developed and studied, with a focus on addressing the security risks and challenges presented by this technology [8],[9],[10],[11],[12]. Such interconnectivity paves the way for arbitrage opportunities across DEXs that operate on distinct blockchains, capitalizing on the variations in pricing across these separate networks. Such an arbitrage that spans multiple blockchains is referred to as *cross-chain arbitrage*. Cross-chain arbitrage is more difficult to detect as it spans multiple chains that are not updated simultaneously. It presents a higher risk as it cannot be performed atomically within a single block on a single chain [13],[14]. The loss of atomicity increases the risk for the token exchange rates to change between transactions, which may cause the arbitrage to fail. Moreover, an arbitrageur (user who conduct arbitrages) must use assets on different chains, increasing the arbitrage complexity. Cross-chain arbitrage is significant in the blockchain ecosystem as it presents many arbitrage possibilities, exploiting price discrepancies between blockchains. Beyond the existing studies on arbitrage within a single blockchain, the literature on cross-chain arbitrage is lacking and primarily concentrates on the formalization of cross-chain arbitrage. Our work aims to fill this gap.

In this paper, *we provide a framework to study cross-chain arbitrage empirically*. We demonstrate its potential by using the framework to analyze in practice cross-chain arbitrage opportunities between two DEXs: PancakeSwap and QuickSwap, which are implemented on two major blockchains BNB Chain and Polygon (Polygon is a side chain to Ethereum). We focus on these blockchains for two reasons: (i) Being among the blockchains with the highest total value locked in them (see Table I). (ii) The ability to access and analyze their data and exchange values. Within these blockchains, the particular DEXs PancakeSwap and QuickSwap were chosen as being dominant DEXs with respect to their value as of September 2023 in their respective blockchains.

II. Background and Related Work

In this section, we introduce some basic terms and concepts from DeFi and overview related work.

A. Glosarry

Smart contracts are programs stored on a blockchain that execute when predefined conditions are met. Smart contracts can be used to create fungible tokens (ERC-20 tokens) beyond the native token Ether. For example, WETH refers to the ERC-20 compatible version of Ether, allowing it to be swapped with other ERC-20 tokens [15], or implemented on other blockchains. We refer to ERC-20 tokens as tokens.

Side chains concept (first proposed in [16]) are separate blockchains that function in parallel to the main blockchain, referred to as the mainnet. The side chain and the mainnet are connected via a two-way-sided bridge that enables the transfer of assets smoothly and securely between the blockchains. Sidechains can have separate block parameters, design, and consensus protocols that mainly aim to solve scalability issues in the mainnet.

BNB Chain comprises BNB Beacon Chain (BC) and BNB Smart Chain (BSC). The BC is responsible for governance, staking, and voting, vital elements in the blockchain operation. The BSC is responsible for the consensus layers and compatibility with different blockchains [17].

Liquidity pools are implemented inside a DEX to enable users to swap tokens. Each pool allows users to swap between a pair of tokens. To swap between two tokens, A and B, first, a liquidity provider (LP) needs to add any amount of token A and a proportional relative amount of token B to a pool so other users can swap between them. In PancakeSwap, the commission fee is 0.25% of the value of every swap made using a pool [18], while it is slightly higher with a fee of 0.3% in QuickSwap [19].

Bonding curve is a concept describing through a formula the inverse relationship between the supply of an asset and its price. This concept underlines that reduced asset quantities lead to price increases [20]. In this paper, we focus on a common bonding curve for two tokens indicating a relation between the amounts of them. For tokens A and B with amounts $\alpha > 0$ and $\beta > 0$ (respectively), it indicates that $\alpha \cdot \beta = k$. For a commission fee λ we denote $\gamma = (1 - \lambda)$. A transaction trading $\Delta\alpha > 0$ of token A for $\Delta\beta > 0$ of token B with λ fee, must satisfy

$$(\alpha + \Delta\alpha \cdot \gamma) \cdot (\beta - \Delta\beta) = k,$$

implying $\Delta\beta = \frac{\beta \cdot \gamma \cdot \Delta\alpha}{\alpha + \gamma \cdot \Delta\alpha}$. DEXs using the bonding curve, maintaining a constant product of token amounts in pools, are known as Constant Product Market Makers (CPMMs). PancakeSwap and QuickSwap are CPMMs.

PancakeSwap and QuickSwap are well-known DEXs on BNB Chain and Polygon, respectively. They have an automated market maker design and follow the bonding curve concept. The DEXs enable the creation of pools that can be used to trade any pair of fungible tokens and provide fees for liquidity provides (LPs). Consequently, they are extensively used and constitute a significant portion of their respective blockchains.

TABLE I
10 Largest Blockchains in Crypto Ranked by total value locked as of September 2023 [23]

Blockchain	Total Value Locked
Ethereum	$47.09B
Tron	$6.54B
BNB Chain	$3.43B
Arbitrum	$1.81B
Polygon	$930.23M
Avalanche	$612.37M
Optimism	$608.7
Cronos	$297.97M
Kava	$267.04M

TABLE II
Basic details of the Analyzed DEXs.

DEX	TVL	Blockchain	Number of pools
PancakeSwap	$2.61B	BNB Chain	17394
QuickSwap	$166.5M	Polygon	2328

We present some approximations of statistics for PancakeSwap and QuickSwap to demonstrate their capacity in Table II. TVL (total value locked) refers to the total amount of money in all pools, and the number of pools as of Jan. 13, 2023. PancakeSwap and QuickSwap are exclusively implemented on BNB Chain and Polygon, respectively.

B. Related Work

CPMMs overview. There is extensive research regarding arbitrage in blockchains and CPMMs. In particular, a few papers analyze theoretical and practical properties of constant product market makers. Angeris et al. [21] analyze constant function market makers, which CPMMs are part of. They show under reasonably general assumptions that constant function market makers tend to report the correct price of assets. They also provide lower bounds, guaranteeing no user can drain the reserves of assets of a given DEX. An analysis of Uniswap is presented in [22]. The paper shows that CPMMs must closely track the reference market price under some common conditions. It also indicates that Uniswap is stable under various market conditions. The DEXs in our paper are CPMMs and, therefore, have the properties as described.

Theoretical and empirical arbitrage analysis in DEXs. Berg et al. [6] perform an empirical analysis to assess the effectiveness of Uniswap and SushiSwap in tracking the reference market. Their analysis involves identifying optimizable trades and cyclic arbitrage opportunities arising from market price inaccuracies. They show that market insufficiencies were especially common in the summer of 2020 and disappeared with time. They suggest that the market becomes less efficient when the prices of cryptocurrencies are highly volatile. Hansson [7] examines how arbitrageurs contribute to price discovery and efficiency in decentralized markets. The study identifies cross-exchange and triangular arbitrages by analyzing transaction data from Ethereum. The findings indicate that arbitrage profits are swiftly realized following price anomalies, showcasing the market's ability to adjust rapidly. Overall, Hansson underscores the role of arbitrageurs in enhancing efficiency within blockchain-based systems.

Boonpeam et al. [24] investigate the potential profits gained through DEXs and suggest an arbitrage system that can identify profit opportunities by trading token routes on different DEXs using statistical techniques. Khetan et al. [25] examine cryptocurrency exchange arbitrage opportunities and propose various strategies for arbitrage. They analyze bitcoin pricing data from Binance, Kucoin, and Coinbase to identify the buy and sell markets for different timeframes and quantify profits from implementing an arbitrage strategy.

Danos et al. [26] present a proposal for modeling the global money market of DeFi using an abstract notion of networks of DEXs. They formalize routing and arbitrage on these networks as convex optimization problems and provide bounds with closed formulas in the case of Uniswap. They propose a theoretical framework for studying cyclic arbitrage and analyze profitability conditions and optimal trading strategies for cyclic transactions. They examine exploitable arbitrage opportunities and market size with transaction-level data from Uniswap V2. Wang et al. [5] introduce a theoretical framework for examining cyclic arbitrage and provide an analysis of the profitability conditions and optimal trading strategies involved. They also investigate the exploitable arbitrage opportunities and market size of cyclic arbitrages by analyzing the transaction-level data from Uniswap V2.

Sjursen et al. [27] try to identify cross-chain arbitrage conducted by users using transaction data between Uniswap on four different blockchains: Ethereum, Arbitrum, Optimism, and Polygon. In contrast, we do not try to identify cross-chain arbitrages done by users. Using a theoretical framework, we analyze cross-chain arbitrage opportunities between the exchanges that users did not utilize.

Overall, previous works studied arbitrages in DEXs within a single blockchain. In contrast, we study arbitrages between DEXs on different blockchains. To the best of our knowledge, our paper is the first to empirically study opportunities for cross-chain arbitrage between DEXs. Cross-chain arbitrage has been mostly formalized, but no work has been done to understand its existence and potential revenue, excluding [27]. Our work aims to provide a theoretical framework to study cross-chain arbitrage empirically and to provide insights into its profitability and the ability to utilize it.

III. A Framework for Cross-chain Arbitrage

This section formalizes the concepts and definitions for the theoretical framework to study cross-chain arbitrage. We use the framework in Section IV to collect cross-chain arbitrages between PancakeSwap and QuickSwap.

A DEX runs over a particular blockchain C and supports a collection of tokens $T = \{t_1, \dots, t_n\}$ where n is the number of tokens. It supports trading between selected pairs of tokens in T such that the set of pairs is $P \subseteq T \times T$. For $p = \{t_i, t_j\} \in P$, one can trade values of token t_i for values of token t_j and vice versa. The trading is supported through a liquidity pool of tokens dedicated to this pair. The amount of the two tokens in the pool can vary over time. The initial values are based on the amounts at the pool establishment.

Definition 1 (Swap): is the exchange of n_i of t_l for n_j of t_r over blockchain C as follows:

$$n_i \cdot t_l \xrightarrow{C} n_j \cdot t_r$$

Definition 2 (Cyclic swap sequence): CSS in short, is a sequence of $m \in \mathbb{N}^+$ token swaps satisfying:

$$\begin{aligned} 1 &: n_1 \cdot t_1 \xrightarrow{C_1} n_2 \cdot t_2 \\ 2 &: n_2 \cdot t_2 \xrightarrow{C_2} n_3 \cdot t_3 \\ &\dots \\ m &: n_m \cdot t_m \xrightarrow{C_m} n_{m+1} \cdot t_1 \end{aligned}$$

A CSS is a type of arbitrage that is considered token-profitable where the arbitrageur earns an additional amount from the value of the token it started with $n_{m+1} > n_1$. In blockchain systems, each transaction incurs gas fees for execution. These fees are on top of the commission charges imposed by DEXs. To determine the gas fees for a transaction, one must multiply the gas price with the transaction gas limit. The gas limit reflects the work needed to execute the transaction.

A CSS is profitable when the token revenue value $(n_{m+1} - n_1) \cdot t_1$ exceeds the fees paid for the CSS. To allow such arbitrage, each token referred on multiple chains must have an implementation on them; for instance, t_1 should have an implementation on C_m and C_1. We consider the different implementations of the same token on different chains to have the same value as they are entwined.

Cyclic cross-chain arbitrage involves more than one chain. There are several types of arbitrages. We focus on cyclic cross-chain arbitrage because of the gap in the literature on this type of arbitrage. We consider cyclic cross-chain arbitrage between two chains. Assume we have m tokens $\{t_i | \ i \in [1, m], m \geq 5\}$, every two consecutive tokens share a pool, and two separate chains C_1, C_2 where t_1 and t_k for some $k \in [4, m-1]$ are implemented on both chains. We denote it as an m-cycle cross-chain. The following CSS is considered an m-cycle cross-chain arbitrage with two chains:

$$\begin{aligned} 1 &: n_1 \cdot t_1 \xrightarrow{C_1} n_2 \cdot t_2 \\ 2 &: n_2 \cdot t_2 \xrightarrow{C_1} n_3 \cdot t_3 \\ &\dots \\ k-1 &: n_{k-1} \cdot t_{k-1} \xrightarrow{C_1} n_k \cdot t_k \\ k &: n_k \cdot t_k \xrightarrow{C_2} n_{k+1} \cdot t_{k+1} \\ &\dots \\ m &: n_m \cdot t_m \xrightarrow{C_2} n_{m+1} \cdot t_1. \end{aligned}$$

We denote cyclic cross-chain arbitrage as cross-chain arbitrage. We calculate the profitability from such an arbitrage by calculating the optimal input amount n_1 that maximizes the difference between the output amount to the input amount $n_{m+1} - n_1$ (we use the results from [5] to do so). We then use n_1 to calculate the revenue. To calculate the profit, we need

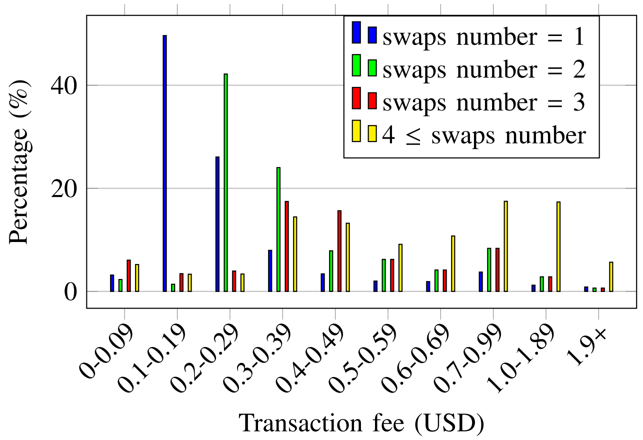


Fig. 1. Distribution of the transaction fee per swaps number in PancakeSwap

to approximate the gas fees for the transaction. We denote it as transaction fee for simplicity.

We use Bitquery [28] to obtain all the gas fees for transactions involving trades on PancakeSwap and QuickSwap between Dec. 12, 2022, and Jan. 13, 2023. Subsequently, This data is used to estimate the gas fees an arbitrager would incur for conducting cross-chain arbitrage during this period. The analysis of cross-chain arbitrage for these dates is presented in Section V.

In Fig. 1, we show the transaction fee by the amount of swaps in the transaction. A higher number of swaps requires more work and, therefore, a higher transaction fee. The transactions with one swap have the lowest average fee, with 0.3 USD per transaction. About 50% of them are between 0.1-0.19 USD. The low average is because they require the lowest amount of work with one swap. The transactions with two swaps have an average fee of 0.42 USD per transaction, and about 40% of them are between 0.2-0.29 USD. The transactions with three swaps have an average fee of 0.68 USD. About 33% of them are between 0.3-0.49 USD. The more swaps, the higher the transaction fee. In total, the average fee of all transactions is 0.36 USD.

We note that cross-chain arbitrage consists of swaps from PancakeSwap and QuickSwap. The transaction fee in QuickSwap is negligible. Most transactions have fees between 0.005-0.049 USD, as shown in Fig. 2. Therefore, the transaction fee for the cross-chain arbitrage is determined by the transaction fee in PancakeSwap. We retrieved the transactions in QuickSwap to approximate the transaction fee for arbitrages that are solely in QuickSwap, which we analyze in Section V. The transactions with three swaps have an average fee of 0.035 USD. About 57% of them are between 0.01-0.049 USD.

IV. Data Collection

In this section, we present the data we collect for the data analysis in Section V of arbitrages in PancakeSwap, QuickSwap, and between them. We note that the arbitrages we collect are arbitrage opportunities in the blockchains at the analyzed timestamps that arbitrageurs did not utilize. To collect arbitrages, we need the state of each DEX at each timestamp. As discussed, each DEX is made of pools. Thus, the state of the DEX at a timestamp is determined by the state of the pools constituting it. To retrieve all the pools of each DEX, we utilize their factory smart contract, primarily used for deploying the smart contracts of pools. The factory smart contract emits a PoolCreated event whenever a pool is created with its deployment address. The sync event is emitted when there is a change in the pool. It includes the amount of each token in the pool, block number, and timestamp. In other words, it provides for the state of the pool.

We collect all the pools created until Jan. 13, 2023. For each pool, we extract its state between Dec. 12, 2022 and Jan. 13, 2023. We only include pools with a sync event during this month to avoid deprecated pools. We denote chain1 and chain2 as the numbers of chains of the analyzed respected DEXs. We use several algorithms to acquire the arbitrages, summarized as Algorithms 1-3.

Algorithm 1 describes the collection of arbitrages. startChain1Time indicates the start time of the analysis. GetChain2Time receives a timestamp and returns the timestamp of a block that was either created at the same time or at the nearest earlier time on chain2. endChain1Time indicates the end time of the analysis. NextTime receives a timestamp

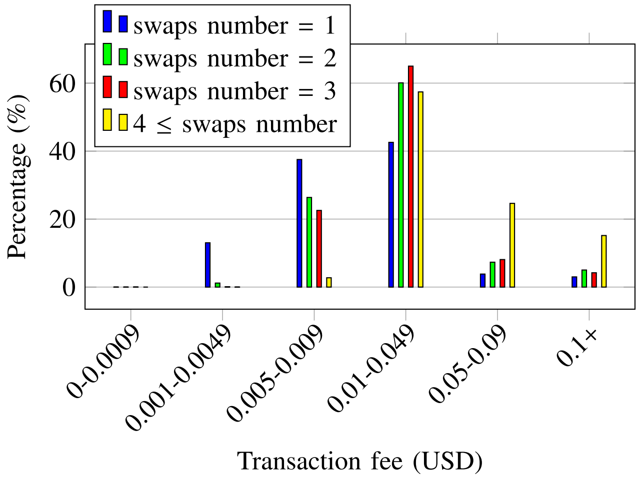
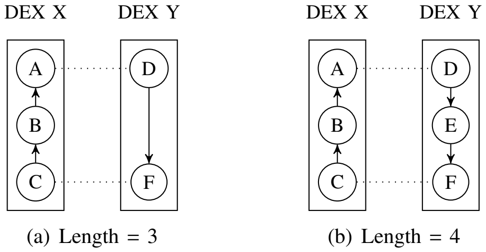


Fig. 2. Distribution of the transaction fee per swaps number in QuickSwap



(a) Length = 3
(b) Length = 4

Fig. 3. Cross-chain arbitrages with lengths three and four. A, B, C, D, E, F refer to various tokens. Solid arrows refer to swaps as part of the cyclic arbitrage. Dashed lines indicate the same token in two DEXs. The length of an arbitrage equals its number of swaps.

Algorithm 1: Collect arbitrages between two DEXs on separate chains

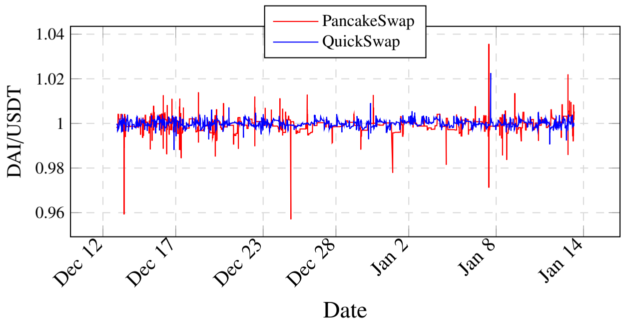
```
$chain1Time \leftarrow startChain1Time$
$chain2Time \leftarrow GetChain2Time(chain1Time)$
while $chain1Time < endChain1Time$ do
    $G \leftarrow BuildGraph(chain1Time, chain2Time)$
    $FindArbitrages(G, MAX(chain1Time, chain2Time))$
    $chain1TimeNext \leftarrow NextTime(chain1Time, chain1)$
    $chain2TimeNext \leftarrow NextTime(chain2Time, chain2)$
    if $chain1TimeNext \leq chain2TimeNext$ then
        $chain1Time \leftarrow chain1TimeNext$
        if $chain1TimeNext == chain2TimeNext$ then
            $chain2Time \leftarrow chain2TimeNext$
    else
        $chain2Time \leftarrow chain2TimeNext$
```

Algorithm 2: BuildGraph $(chain1Time, chain2Time)$

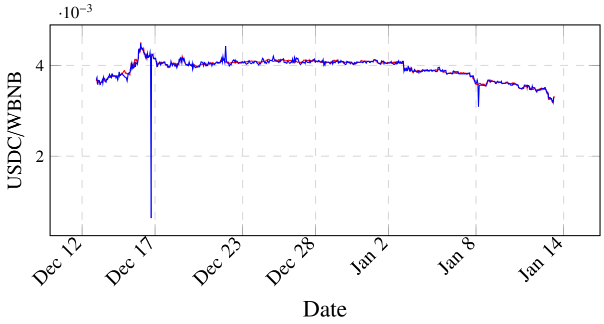
```
Init an empty graph $G$
for $pool$ in $Pools$ do
    if $pool$ in $chain1Pools$ then
        $e \leftarrow GetClosestState(pool, chain1Time, chain1)$
    else
        $e \leftarrow GetClosestState(pool, chain2Time, chain2)$
    Add $e$ to $G$
return $G$
```

Algorithm 3: FindArbitrages $(G, timestamp)$

```
for $tokenS$ in $sharedTokens$ do
    for $tokenM$ in $sharedTokens$ do
        for $Ch$ in $[chain1, chain2]$ do
            $Ch' = chain1$
            if $Ch == chain1$ then
                $Ch' = chain2$
            $pathsStart \leftarrow$
              $PathsUpLen2(tokenS, tokenM, Ch)$
            $pathsEnd \leftarrow$
              $PathsUpLen2(tokenM, tokenS, Ch')$
            for $pathS$ in $pathsStart$ do
                for $pathE$ in $pathsEnd$ do
                    if $Arbitrage(pathS, pathE, Ch)$ then
                        SaveArbitrage($pathS$, $pathE$,
                          $timestamp$, $Ch$)
```



(a) The ratio between DAI to USDT



(b) The ratio between USDC to WBNB

Fig. 4. Ratios between DAI to USDT and USDC to WBNB in both DEXs respectively

and a chain number and returns the subsequent timestamp of a block created on the specified chain after the provided timestamp. For each timestamp, we describe the state of the two DEXs as a graph. Vertices are tokens and edges indicate the amount of each of the two connected tokens in the pool between them.

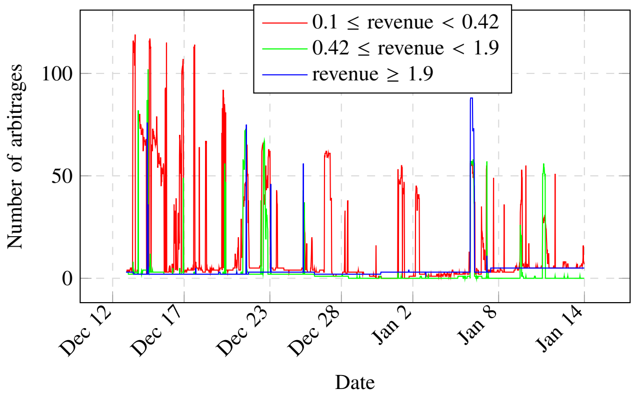
Algorithm 2 describes the building of the graph. Pools refers to all the pool contracts in the DEXs and chain1Pools refers to the pool contracts in the DEX on chain1. GetClosestState receives a pool contract, timestamp, and chain number and returns the closest smallest state of the pool using the sync events (the amounts of each token in the pool).

Algorithm 3 receives a graph and saves all arbitrages by timestamp. sharedTokens refers to tokens that have an implementation on both chains. PathsUpLen2 returns all paths, with a maximum length of two, between vertices on a given chain. Arbitrage returns whether the arbitrage is profitable and valid (involving more than two swaps). SaveArbitrage receives the arbitrage, timestamp, and the starting chain of the arbitrage, and based on these parameters, it saves the arbitrage. Using these algorithms, we can acquire up to 4-cycle cross-chain arbitrages between two DEXs.

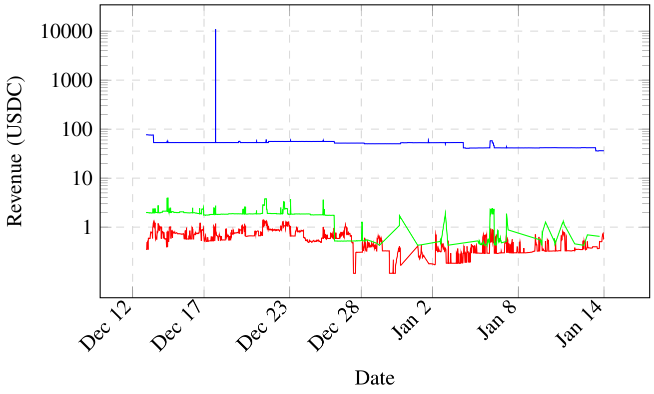
Fig. 3 illustrates the structure of the cross-chain arbitrages between the two DEXs. To understand the relationship between cross-chain arbitrage and single-chain arbitrage, we collect arbitrages of length three from each DEX separately. The considered arbitrages are in the form $A \rightarrow B \rightarrow C \rightarrow A, A \in sharedTokens$. They were considered for their joint tokens with the cross-chain arbitrages and similar structure. We use public APIs from BscScan and polygonscan to get the addresses of the pools, Bitquery to query for the timestamps, and Moralis to get the sync events and metadata on the tokens.

V. Data analysis

This section provides an analysis of the arbitrage opportunities data that we collect. We use our framework to collect cross-chain arbitrage opportunities between PancakeSwap and QuickSwap. For simplicity, we divide this section into three subsections. In the first subsection V-A, we present an intuition for arbitrage possibilities between PancakeSwap and QuickSwap. The second subsection V-B analyzes the profitability and number of arbitrages, while the third subsection V-C analyzes the duration of cross-chain arbitrages.



(a) Number of arbitrages by date between PancakeSwap and QuickSwap



(b) Total potential revenue over all arbitrages by date between PancakeSwap and QuickSwap

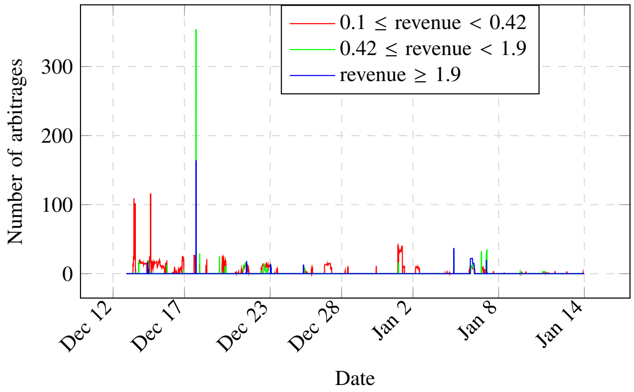
Fig. 5. The number and revenue of arbitrages between PancakeSwap and QuickSwap

Along the section, the revenue amounts are calculated based on arbitrages that do not share a pool. This is to avoid summing up revenues that utilize the same price discrepancy more than once. In contrast, we count all possible arbitrage opportunities because price discrepancies can be utilized in different ways. The revenue is measured in USDC at the exchange rate at the time of the arbitrage within the exchange. Transaction fees are measured in USD. USDC is a cryptocurrency that aims to have the same value as USD in close proximity. This allows easy joint consideration of fees (in USD) and revenues (in USDC).

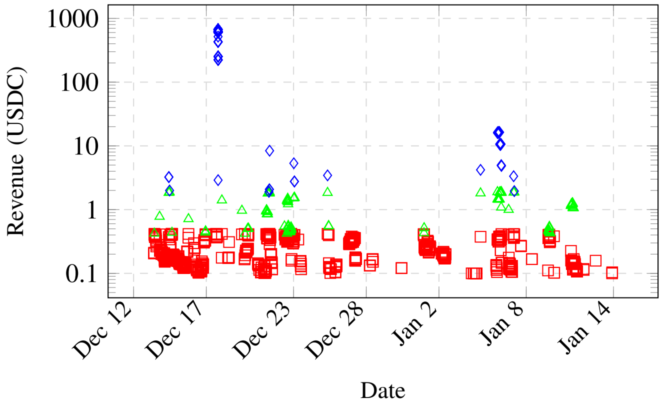
A. *Tokens comparison*

The following figures present the ratios of tokens implemented at each chain and traded in the DEXs. Fig. 4(a) shows over time the price of a stablecoin named DAI in terms of another stablecoin USDT. In each DEX, the price remains close to 1, implying a slight difference in the prices over the two DEXs. For most of the time period, the price ratios of the two stay within a range of 0.99 and 1.01.

In Fig. 4(b) the ratios between the tokens are highly correlated following the high trade rate in both DEXs. We use the difference between the exchange rates of tokens shared between the chains, combined with different exchange rates of tokens not necessarily shared to find cross-chain arbitrages.



(a) Number of arbitrages by date between PancakeSwap and QuickSwap



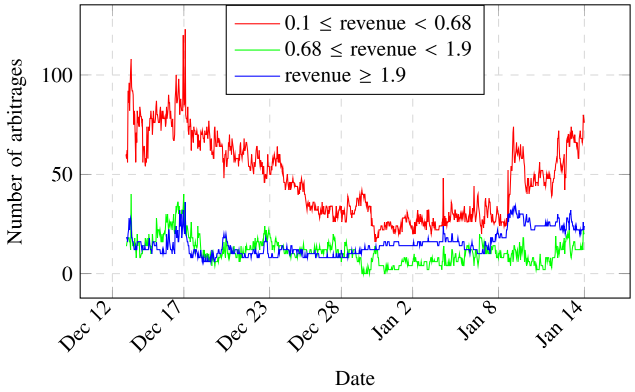
(b) Total potential revenue over all arbitrages by date between PancakeSwap and QuickSwap

Fig. 6. The number and revenue of arbitrages between PancakeSwap and QuickSwap, which do not share pools with existing arbitrages in each DEX

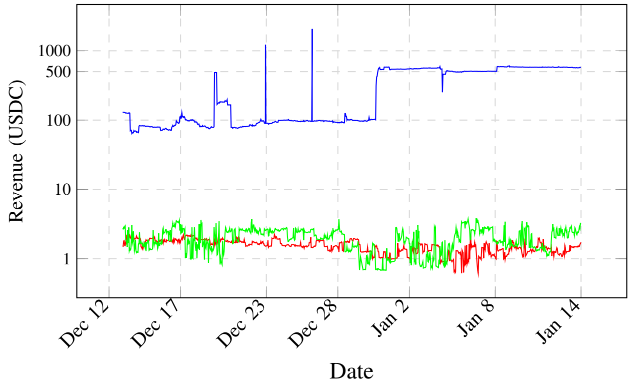
B. *Revenue and number of arbitrages*

For each of the following figures, we present the revenue with respect to the approximation of the transaction fee required to complete the arbitrage. We divide the fee into three categories: lower bound, average, and high bound. Those categories are based on Fig. 1 and Fig. 2. Arbitrages in PancakeSwap and QuickSwap require three swaps to complete. While, between PancakeSwap and QuickSwap, two swaps are required at most at each exchange to complete the arbitrage. As discussed, the number of swaps affects the transaction fee. Therefore, the values of the categories are appropriate to the number of swaps.

We denote A_P as a token A in PancakeSwap and B_Q as token B in QuickSwap. In Fig. 5 until Dec 17, the revenue spans between 50 to 80 USDC. This is mainly due to discrepancies in $U_P{-}USDC_P$, $U_P{-}USDT_P$. On Dec 17, the revenues surpassed 1,000 USDC and peaked at approximately 10,000 USDC. Arbitrages that use the pool $WBNB_Q - USDC_Q$ combined with pools in PancakeSwap produce high revenue, thousands of USDCs. For example, $USDC_P \rightarrow BUSD_P \rightarrow WBNB_P - WBNB_Q \rightarrow USDC_Q$ produce a revenue of 10,877 USDC. This amount of revenue is not reached in PancakeSwap and QuickSwap even though the discrepancy exists in one of the

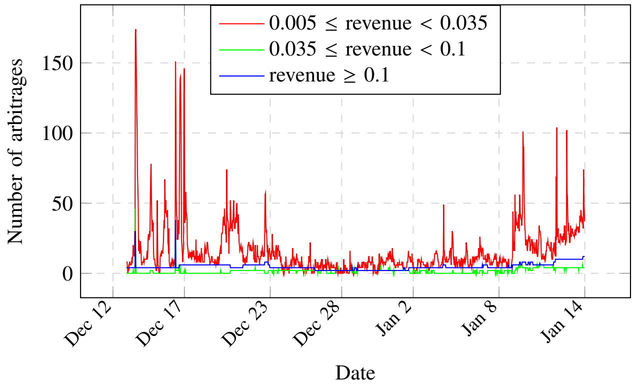


(a) Number of arbitrages by date in PancakeSwap

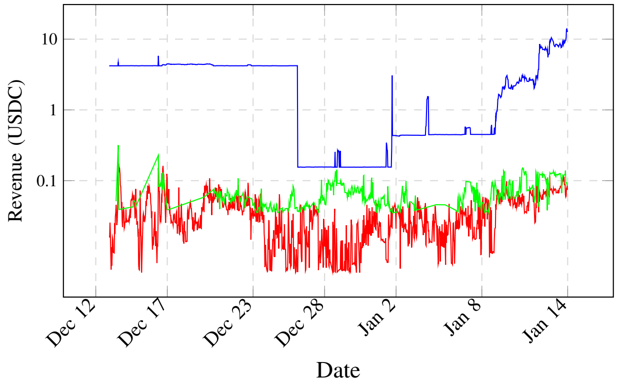


(b) Total potential revenue over all arbitrages by date in PancakeSwap

Fig. 7. The number and revenue of arbitrages in PancakeSwap



(a) Number of arbitrages by date in QuickSwap



(b) Total potential revenue over all arbitrages by date in QuickSwap

Fig. 8. The number and revenue of arbitrages in QuickSwap

DEXs as this arbitrage does not exist in Fig. 6. Following Dec 17, the revenue stabilizes at around 40 USDC mainly due to the discrepancy in $U_P - USDC_P, U_P - USDT_P$.

In Fig. 7 on Dec 19, there is a spike in revenues. This is due to a discrepancy involving $GOTCHI_P$. The spike with revenue of around 1,000 USDC on Dec 22 is due to a discrepancy involving ATP_P, and the one with revenue of around 2,000 USDC on Dec 26 is due to a discrepancy involving JTS_P. After Dec 30, the revenue stabilizes around 500 USDC mainly due to discrepancy involving FLD_P.

The similarity between PancakeSwap and the cross-chain is reasonable because the cross-chain arbitrage utilizes price differences in each DEX. The cross-chain revenue is much higher than the revenue in QuickSwap, as shown in Fig. 8. This is due to the fewer resources and pools QuickSwap has, as shown in Table II, and the potential revenue within is much smaller than the high-resource PancakeSwap. In Fig. 8 until Dec 26, the high revenue is primarily due to discrepancy involving KIJ_Q. From Jan 9, it is primarily due to a discrepancy involving 4.0_Q.

In Fig. 5, the revenue does not surpass the revenues in PancakeSwap at several time frames. This is mainly due to the limitation in the length of the arbitrage and the resources in QuickSwap. For example, on Jan 13, the revenue in PancakeSwap reaches approximately 500 USDC mainly for the arbitrage $USDT_P \rightarrow BUSD_P \rightarrow FLD_P \rightarrow USDT_P$. In cross-chain, such revenue is not reached on Jan 13. To reach such revenue by utilizing this arbitrage in cross-chain, we need to analyze its form as it was in cross-chain. The cross-chain arbitrage has a path in QuickSwap and a path in PancakeSwap, where each path constitutes two swaps at most. Therefore, for the arbitrage to appear as cross-chain arbitrage, the path in PancakeSwap must be $BUSD_P \rightarrow FLD_P \rightarrow USDT_P$, meaning $BUSD$ and $USDT$ must be shared with QuickSwap. However, in all the pools in QuickSwap, there is only 10.57 BUSD, thus deterring the full utilization of the arbitrage. If the cross-chain arbitrage had been longer, then the arbitrage could have been fully utilized because there is not a shortage of $USDT$ and $USDC$ in QuickSwap in that timeframe, making $USDC_P \rightarrow BUSD_P \rightarrow FLD_P \rightarrow USDT_P$ possible where $USDC$ and $USDT$ are shared.

Fig. 6 shows arbitrages that do not share a pool with existing arbitrages within each DEX. This indicates a potential addition for revenue that is not utilized in each DEX separately. The revenue spans primarily between 0.1 to 10 USDC, where even a value over 1,000 USDC is reached.

The ability of cross-chain arbitrage to utilize the price discrepancies depends on the arbitrage complexity and the amount of resources in each DEX. We show that it offers a way to gain profits that do not necessarily exist in each DEX separately and enhance existing ones.

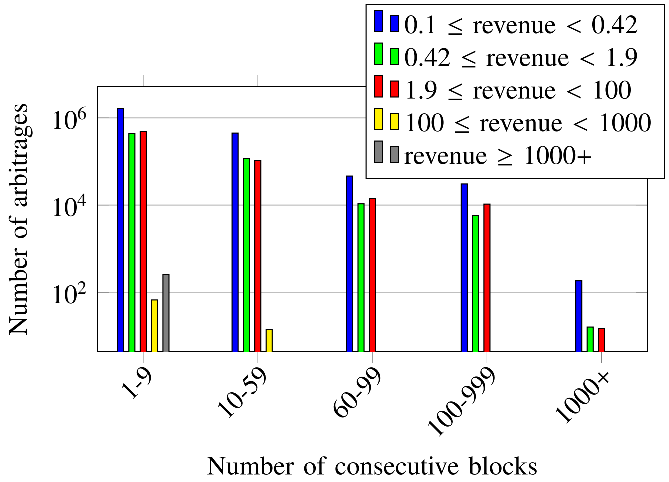


Fig. 9. Distribution of arbitrage duration (in units of consecutive blocks) as a function of its revenue. between PancakeSwap and QuickSwap

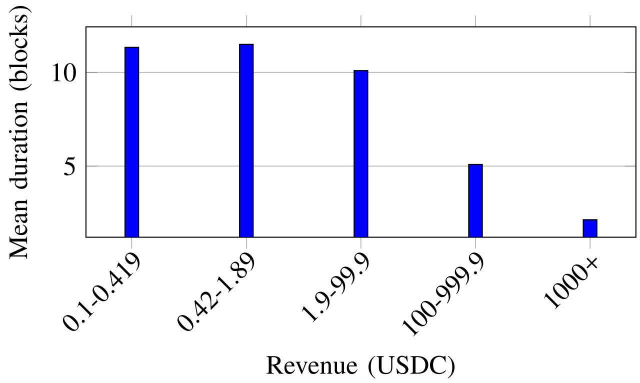


Fig. 10. Distribution of the mean arbitrage duration (in units of blocks) per revenue between PancakeSwap and QuickSwap

C. Duration of arbitrages

We define the duration of cross-chain arbitrage as the number of consecutive blocks that the arbitrage exists with the same amount of revenue. This definition is reasonable because we want to measure the duration an arbitrageur can conduct a cross-chain arbitrage and gain the arbitrage revenue. We denote the amount of time before a transaction is added to the blockchain as transaction time. We approximate the transaction times on BNB Chain based on [29] and on Polygon based on [30]. In [29] and [30], the amount of time for a transaction to be included in the blockchain is presented with three categories: standard, fast, and rapid. Each category describes the gas price compared to the transaction time, where a lower transaction time requires higher gas price. As discussed, the transaction fee is calculated by multiplying the gas price with the gas limit, and therefore, we can deduct the transaction fee compared to the transaction time.

On the BNB Chain, transaction times typically range from 5 to 60 seconds; this correlates to 2 to 20 blocks, with a new block every 3 seconds. On Polygon, transaction times are similar, but with blocks every 2 seconds; this correlates to 2 to 30 blocks. Transaction time has a high variance and mainly depends on network traffic and gas prices. Generally, higher transaction fee can result in lower transaction time.

In Fig. 9, the total number of arbitrages with revenue between 0.1 to 0.42 USDC is the largest in every duration group. This is due to the proximity of those arbitrages to the transaction fee, making them highly volatile to market changes on the lower end of the duration group and less likely to be extracted on the higher end. Although the average number of consecutive blocks is relatively low, 11.34 as shown in Fig. 10, there are 76,980 arbitrages with a duration longer than 60 blocks. In 60 consecutive blocks, there are 36 polygon blocks (60% of these blocks) and 24 BNB Chain blocks. This correlates to the longest approximation of 20 blocks in BNB Chain and 30 blocks on Polygon.

The arbitrages with revenue 0.42 to 1.9 USDC follow the same principles as those with revenues of 0.1 to 0.42 USDC. However, as the achievable revenue tends to be higher than the transaction fee, they are more worthwhile to utilize. A higher transaction fee can be paid and still gain a profit. The arbitrages with revenue between 100 to 1,000 USDC with average consecutive blocks of 5.09, as shown in Fig. 10 have high revenue. Therefore, a high transaction fee can be paid to obtain a profit from arbitrages with a duration of 1-10 blocks. In summary, high revenues are associated with shorter transaction times, but this can be mitigated by paying a higher transaction fee. Moreover, there are approximately 118,127 arbitrage opportunities that span a duration of more than 60 blocks.

VI. Conclusions And Further research

The blockchain ecosystem is evolving to contain multiple chains. Multiple DEXs are being developed across these chains, leading to high availability of assets across different chains. This development offers diverse trading methods and paves the way for new arbitrage opportunities.

Through an experimental study, we show that cross-chain arbitrage potentially provides opportunities for arbitrageurs to utilize and gain profits that do not necessarily exist in each DEX separately and enhance existing ones. The properties of the DEXs, the arbitrage complexity, and the network state play a critical role in establishing cross-chain arbitrage. As far as we know, we are the first to show an empirical analysis of cross-chain arbitrage opportunities in terms of quantity and revenue. We lay the foundations for further research on cross-chain arbitrages. Open questions for further research are:

- Is there a correlation between the properties of DEXs and the amount and revenue that can be established from cross-chain arbitrages?
- How can we investigate cross-chain arbitrages in DEXs that are not CPMMs?
- To what extent can we minimize the risks associated with cross-chain arbitrage?
- Can we further research or find different methods to extract value between different chains?

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